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FINAL REPORT

DESIGN, DEVELOPMENT, FABRICATION, TEST, AND DELIVERY OF ELECTROTHERMAL ENGINE SYSTEMS

Prepared for

National Aeronautics and Space Administration

November 1967

Contract NAS3-7934

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Spacecraft Technology Division
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ABSTRACT

This document is the final report on a program for the design, development, fabrication, test, and delivery of an electrothermal three-axis spacecraft attitude control and four-direction station-keeping system. Qualification and performance tests have demonstrated the specified control and operation of a fully active resistojet propulsion system following launch and space environmental testing. The system is composed of the following subsystems: ammonia propellant storage; thrust pressure regulation; electrothermal resistojet thrustors; control logic; and power and signal conditioning. The system was designed and developed for a hypothetical spacecraft in the 300 to 1200 pound class. A principal system feature is the adaptability of the several subsystems with minimum effort to meet the auxiliary propulsion requirements of an actual spacecraft.

EDITED BY:
EDITORIAL SERVICES SECTION
F. J. KLAISS

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I. INTRODUCTION

A. PROGRAM OBJECTIVES

The overall objective of the present program was to design, develop, fabricate, and test a flight-quality, ammonia-fueled resistojet thrustor system. The thrustor system was defined to include logic controls, power and signal conditioning, and a zero-gravity propellant storage and feed system. The system is suitable for the three-axis control and four-direction station-keeping of satellites in the 300- to 1200-pound class. The thrustors are resistojets, fast heat-up type, with a nominal thrust of 0.40 x 10^{-3} pound and a nominal specific impulse of 150 seconds.

B. PROGRAM ORGANIZATION

This program originates from the Electric Propulsion Office of the NASA/Lewis Research Center. Mr. Henry Hunczak is the Nasa/Lewis Research Center Project Manager. The Avco/SSD Project Director was Dr. R. R. John; the Project Manager was T. K. Pugmire; and principal contributors were A. Buczynski, E. Comfort, W. Davis, R. Ingemi, M. Lambert, J. Olbrych, R. Shaw, and L. Smith.

C. REPORTING PERIOD

This is the final report on Contract NAS 3-7934, entitled "Design, Development Fabrication, Test, and Delivery of Electrothermal Engine Systems," and covers the period from December 1965 through November 1967.

D. TECHNICAL SUMMARY

A three-axis attitude control and four-directional station-keeping system, which makes use of a fast heat-up resistojet as the basic propulsion element, has been designed, fabricated and qualification tested. The thrustors operate at a nominal thrust of 0.40 x 10^{-3} pound and a specific impulse of 150 seconds. They require less than 7.5 watts of input power when operating. The attitude control system has separate control logic and power and signal conditioning packages for each axis. The control logic system has been designed to make it possible to adjust the basic control circuit parameters, including hysteresis between thrust-off and thrust-on and the lead-network time constant. A three-axis sensor has been developed for ground test of the attitude controls. Station-keeping units, each containing two thrustors, have been provided for two of the three axes. Propellant storage for 56 pounds of liquid ammonia, with an adjustable thrust level, 50-25,000 x 10^{-6} pound and zero "g" propellant feed, is provided with the system.

The program consisted of three major phases. The first was an extensive development and design phase, including development of the electronics power-signal conditioning and controls, with a full breadboard system, elastomer material development and test for compatibility with the ammonia propellant, development and design of a reliable zero "g" pressure regulation and feed system, and determination of thrustor design parameters and characteristics. The second phase was component and subsystem testing and qualification. The third and last phase was system performance and environmental qualification testing.

II. SYSTEM DESCRIPTION

A. INTRODUCTION AND BACKGROUND

The electrothermal engine system developed and tested is a fully active, three-axis spacecraft attitude control and four-direction station-keeping system. It includes all of the components and subsystems required to control the position and orientation of a hypothetical stable-platform type satellite. An adaptive feature has been built into the system such that the several separate subsystems can be modified or adjusted with a minimum of effort to meet a wide range of requirements of an actual spacecraft.

The fast heat-up type resistojet thrustor and the principal control and power and signal conditioning electronic circuits are similar to those developed under a previous contract (NAS 3-5908), reference 1. System and subsystem specifications have been reported previously in Avco/SSD Semiannual Report on Contract NAS 3-7934 (August 1966), reference 2.

The following subsections summarize descriptions of the power and signal conditioning, logic, station-keeping control, propellant storage and feed systems, and thrustor assembly. Component and subsystem test specifications are outlined in Section III. System performance and environmental tests are found in Section IV.

B. POWER-SIGNAL CONDITIONING AND CONTROLS

1. General Description

A schematic diagram of the system controls, a coupled simulated orientation reference and sensor, and ground command and telemetry interface are shown in Figure 1. The three-axis ground test orientation reference and sensor were developed to simulate the separate light sources and sensors that would be used for each axis in flight. A single unit was designed to provide three-axis orientation and rate sensing for test convenience. This sensor requires only a single light source. The signals from the light sensor are transmitted to separate attitude control logic modules for each axis through separate junction boxes. Two types of junction boxes have been developed, one with adjustable controls of the basic control circuit parameters (for system adaptation for difference applications and control requirements) and the other of flight-quality into which the fixed controls of lead-network time constants and hysteresis would be incorporated as a function of system application to meet the requirements of an acutal spacecraft.

Separate power and signal conditioning modules are used for ground and/or logic module command of thrustor operation for each attitude control axis. (This feature would permit use of a single module for a number of applications when automatic and ground command control is required for two thrustors such as for spacecraft spin control or single-axis orientation.)

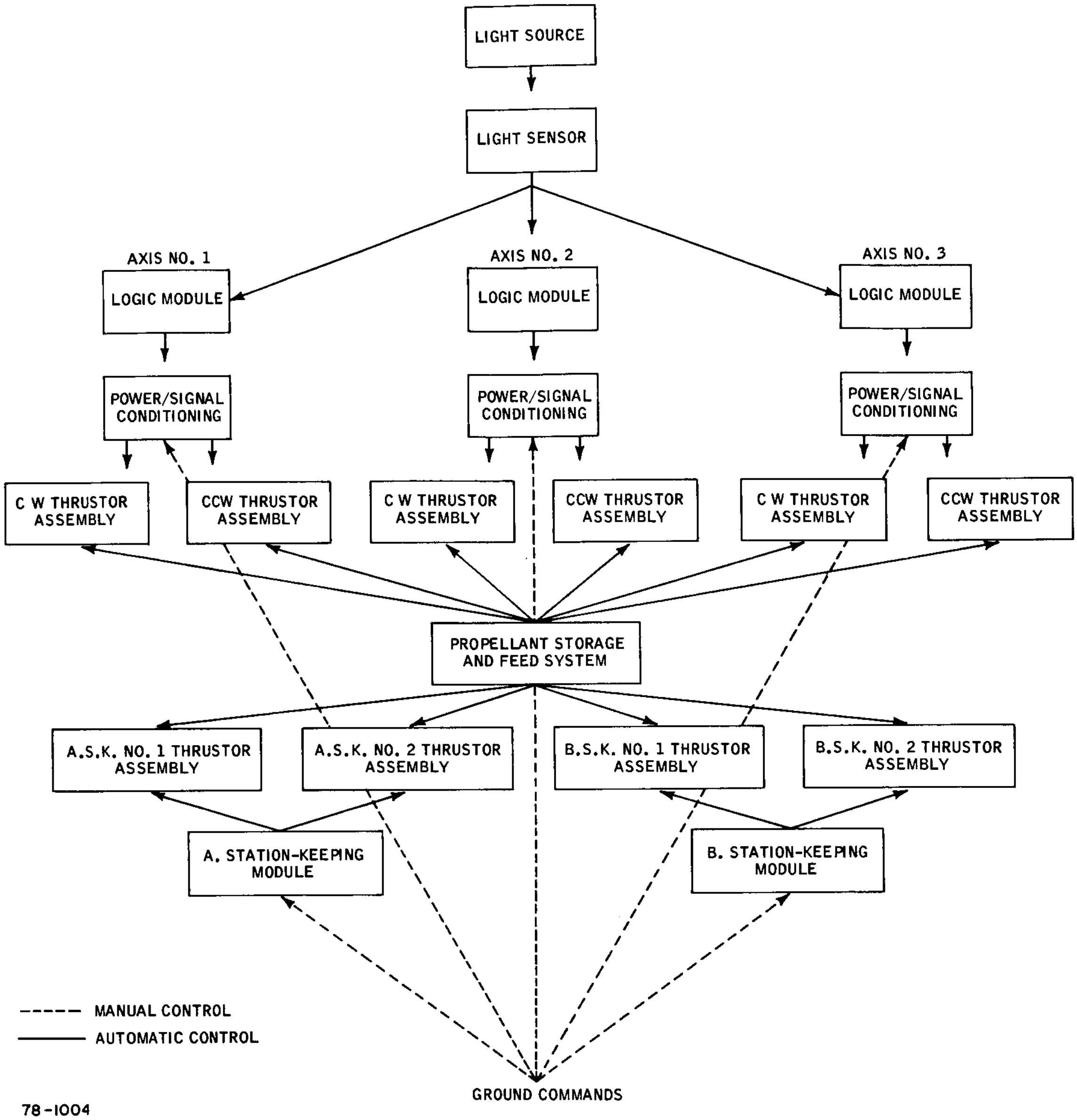

Figure 1 SCHEMATIC DIAGRAM OF THE OVERALL SYSTEM CONTROLS

Two modules have been provided for power and signal conditioning and ground command for each pair (two directions) of station-keeping thrustors. These modules differ from the attitude control conditioning and control modules in that they have single input control for each thrustor; the attitude control modules have two inputs for each thrustor. (These modules could also be used for a number of applications as they provide power conditioning for operation of the two thrustor heaters, pressure transducers, telemetry signal conditioning for the measured signals of pressure, thrustor heater voltage and current, and flow valve voltage as separate control of the thrustor heating and propellant flow.)

A single module is required for the propellant storage and feed system. This module may be used in conjunction with any or none of the other thrustor control modules. The module provides power conditioning for three pressure transducers, a thermistor circuit, and the propellant pressure regulation valves-pressure switches. It also provides telemetry signal conditioning for the pressure, temperature, and regulating valve measurements.

2. Control Logic Module

A functional diagram of the control logic system is shown in Figure 2. A photograph of a module is shown in Figure 3. The control function, Z (t), is generated by the lead network. The lead network takes the sensor signal, θ (t), and generates a control function, Z (t), which is proportional to the sum of the vehicle position, θ (t), and rate, θ (t). The lead network has been described previously (reference 2). As shown in Figure 2, the control function, Z (t), is then fed into a switching network which controls the operation of the appropriate engine.

The basic switching network is also shown in Figure 2. Basically, the control method is that a thrustor is selected and operated continuously as long as a specified angular plus rate error is exceeded. The control logic systems for the different axes operate completely autonomously; there are no interconnections between the individual axes. Referring to Figure 2, the input signal from the sensor passes through the lead-lag network and then simultaneously through an absolute magnitude detector and a polarity detector. If the signal from the absolute magnitude detector (and hence from the lead-lag network and the sensor) is above a certain level, it will trigger the Schmitt Trigger and send a +5-volt digital signal out of the package. The polarity detector provides two digital outputs. One of the outputs is at +5-volts whenever the input signal is positive, and at 0 volts whenever the input signal is negative; the second output is +5-volts whenever the input signal is negative, and at 0 volts whenever the input signal is negative. The Schmitt Trigger actuates the valve-heater circuit, and the polarity detector signals the appropriate thrustor to go on.

As indicated previously, the basic parameters of the control logic system can be varied by means of an adjustment-junction box. This box is shown in dashed lines. The basic parameters which can be varied by the adjustment box are shown in Table I.

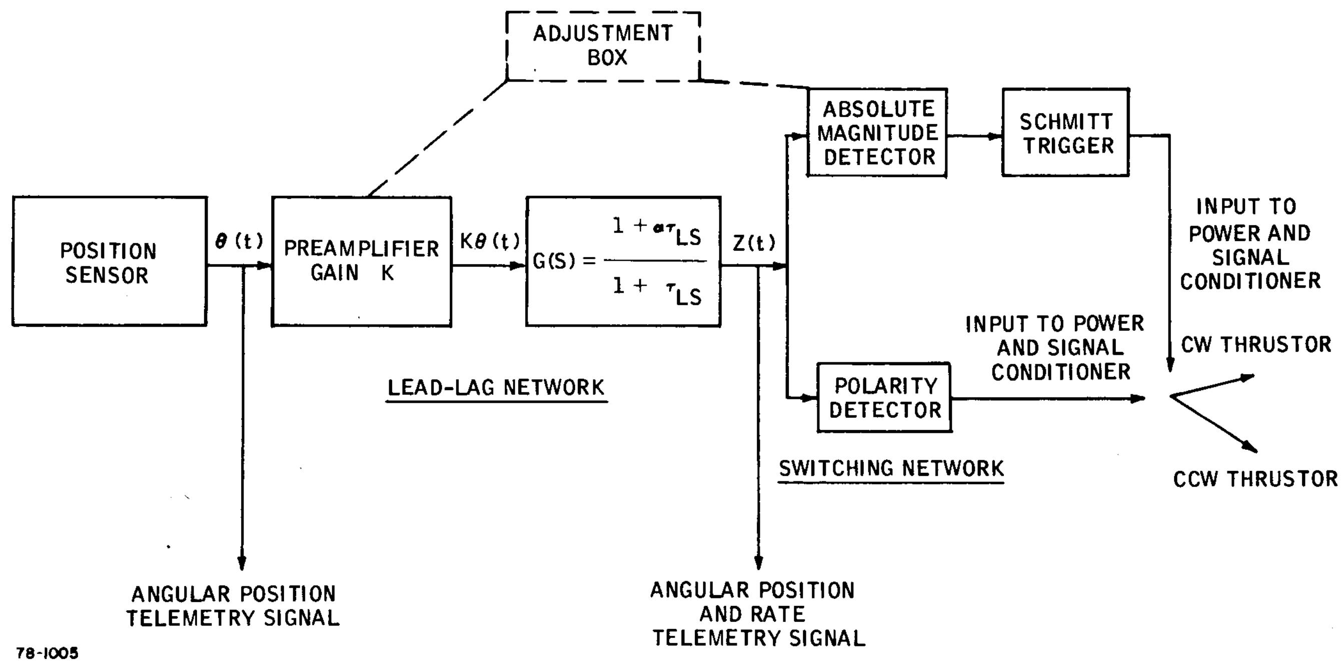

Figure 2 FUNCTIONAL DESCRIPTION OF THE CONTROL LOGIC MODULE

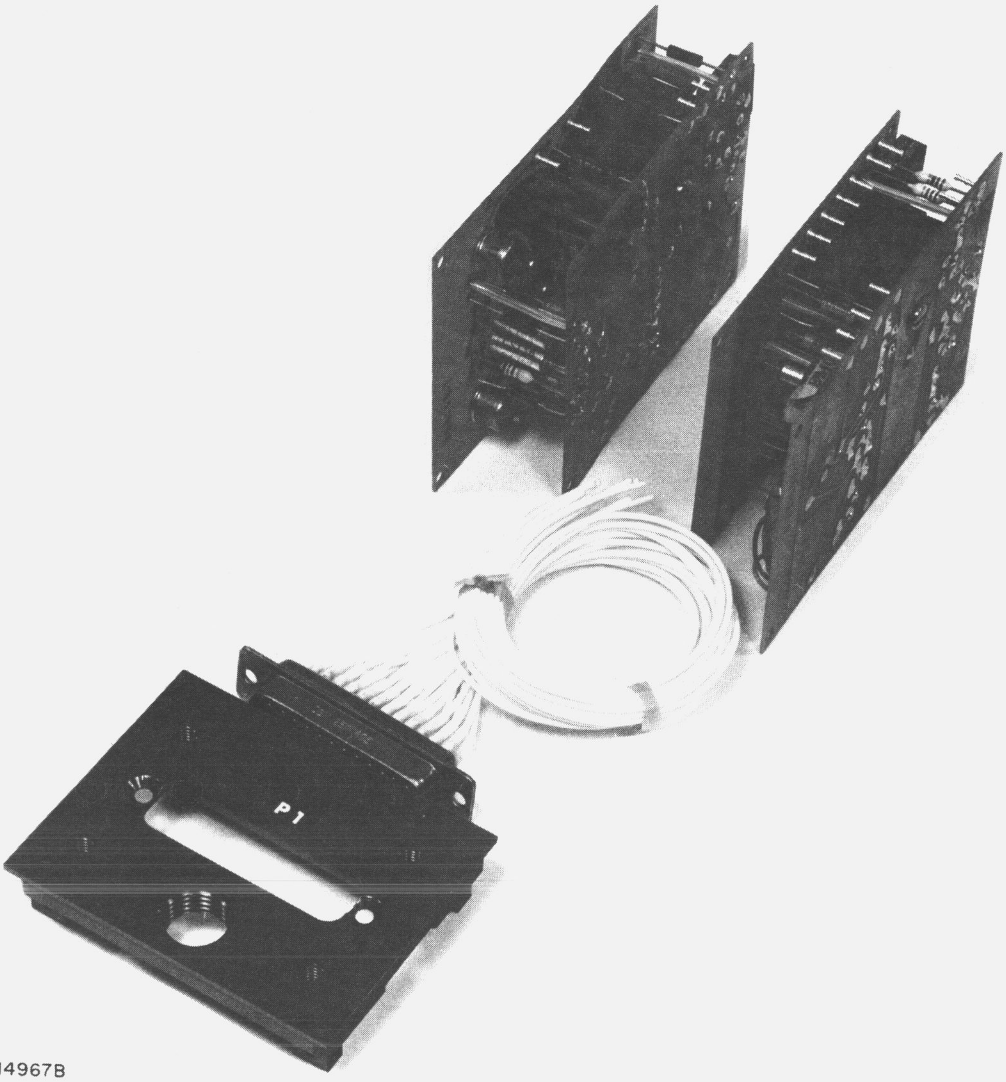

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Figure 3 LOGIC MODULE

TABLE I

RANGE OF ADJUSTMENTS FOR THE CONTROL LOGIC MODULE

Variable Input Voltage to Switch the Trigger Circuit	$\pm$ 0.10 to ± 10 volts
Hysteresis Between Thrust-On and Thrust-Off	5 to 40 percent
Lead-Network Time Constant	2 to 100 seconds

The basic trigger level of the Schmitt Triggers is held constant, while the voltage divider, shown in the adjustment box, is adjustable to permit triggering at sensor input levels (0-rate) from ± 0.1 volt to ± 10 volts. For example, an angular displacement of ± 1 degree might correspond to ± 0.1 volt on one sensor and ± 10 volts on another sensor; the variable voltage divider makes it possible to accommodate a wide variety of sensors.

To avoid control logic instabilities, it is found necessary to incorporate an adjustment for hysteresis between the thrust-on and the thrust-off signal voltage level. The turn-off level may be externally adjusted from 5 to 40 percent lower than the turn-on level. There are a total of eight selections for hysteresis. The significant transfer function of the control logic system is that of a lead network for stabilization and a lag or upper frequency rolloff for noise attenuation. The lead or lower frequency time constant is adjustable in approximately 12 discrete steps from 2 to 100 seconds. The lag or upper frequency rolloff time constant is variable to ± 10 percent of the adjustment time constant. Provision is also included to operate with two discrete values of the transfer function damping factor, i.e., α = 0.10 and 0.033.

The inputs and outputs from the control logic module are summarized in Table II and Figure 2.

TABLE II

INPUT AND OUTPUT CHANNELS FOR THE CONTROL LOGIC MODULE

Input Channels

1. 28 volts $\pm$ 10-percent Battery Power
2. Sensor Input (± 0.10 to ± 10 volts)

Output Channels

1. Angular Position, θ
2. Angular Position + Rate, $\theta + \dot{\theta}$ (analog)
3. Thrustor ON Command (Schmitt Trigger)
4. CW Engine Selection (Polarity Detector)
5. CCW Engine Selection (Polarity Detector)
6. Battery Current for Single-Axis Operation

As shown in Figure 2, the output signals for angular position and rate are passed directly to the telemetry package; the thrustor on-command and thrustor selection are passed directly to the power and signal conditioning package.

The model specifications for the control logic module are presented in Appendix A of reference 2.

3. Power and Signal Conditioner Module

The power and signal conditioner contains the necessary circuitry to supply power to the resistojet heater elements, flow valve, and pressure transducer. It also conditions performance signals for telemetry. A schematic diagram of the telemetry and control functions with the power and signal conditioning modules is shown in Figure 4 and a photograph of the module in Figure 5.

Because of the low resistance of the resistojet heater elements (order of 0.10 ohm), it has been found necessary to convert the basic dc input power to 5000 cps ac and then to step down to the required heater voltage (order of 1 volt) by means of a transformer. A schematic diagram for this operation is shown in Figure 6. The power input to the heater elements is thus alternating rather than direct current. A separate transformer is provided for each heater element.

The power and signal conditioner contains all the necessary circuitry to supply a nominal 7.5 watts to the resistojet heater elements, which have a nominal resistance of 0.10 ohm. Referring to Figure 4, the power conditioner operates in the following manner: The proper heater and valve, i.e., clockwise or counter-clockwise, are selected by the + 5-volt signal from the polarity detector in the control logic package. The + 5-volt thrust-on signal from the Schmitt Trigger in the logic package activates the oscillator circuitry, thereby turning the heater on. The thrust-on Schmitt Trigger signal also activates the gas flow valves one second after the heaters are energized. Power transformers are located directly at the thrustors.

Provision is also included in the power and signal conditioner package to operate the thrustors without any power to the heater element, i.e., cold operation, and to have manual operation of the clockwise and counter-clockwise thrustors. The manual thrustor ON/OFF control channel is of the "toggle" type. The first application will turn the desired thrustor on, the second application will turn it off, the third application on, etc. The automatic control channel is set in the off position by activation of either of the manual thrustor ON/OFF commands. The input channels for the power and signal conditioner package are shown in Figure 4.

A total of seven signals are monitored from each power and signal conditioning package.

The model specifications for the power and signal conditioning module are presented in Appendix B of reference 2.

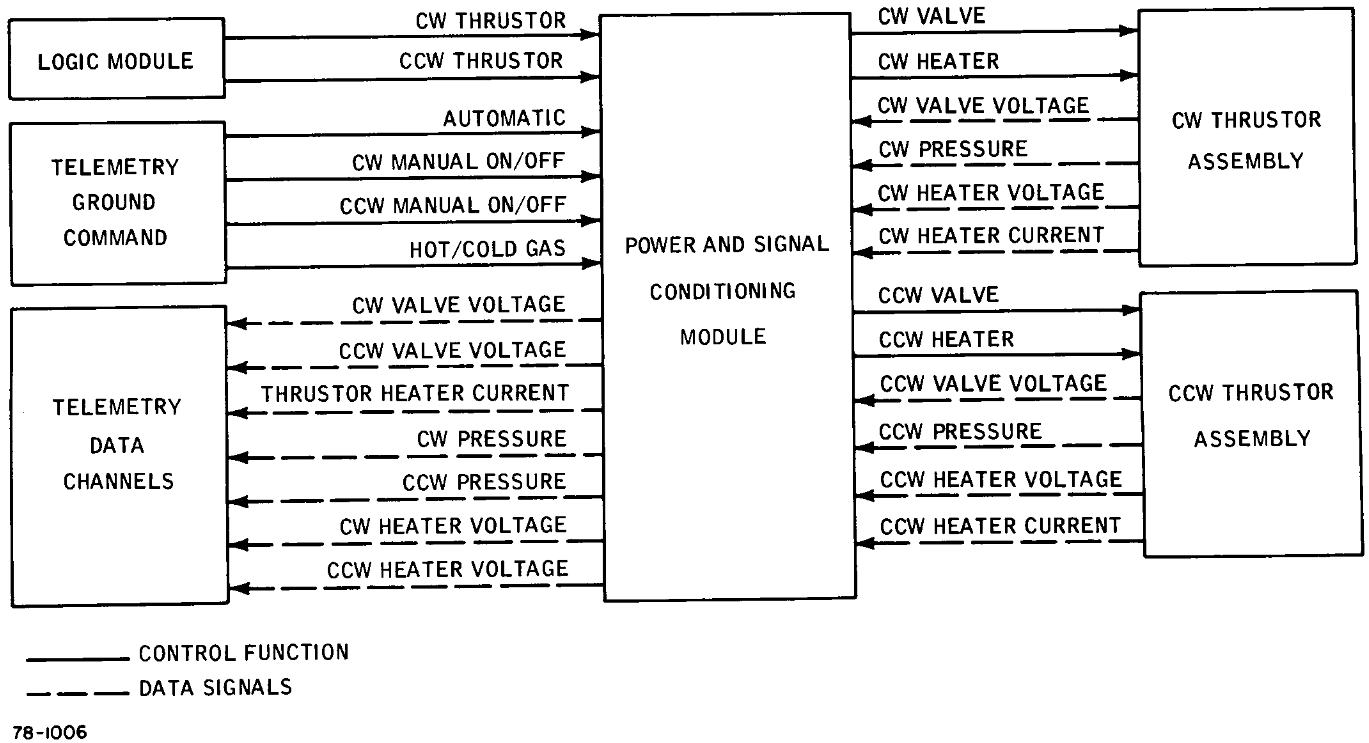

Figure 4 SCHEMATIC DIAGRAM OF TELEMETRY AND CONTROL FUNCTIONS WITH THE POWER AND SIGNAL CONDITIONER MODULE

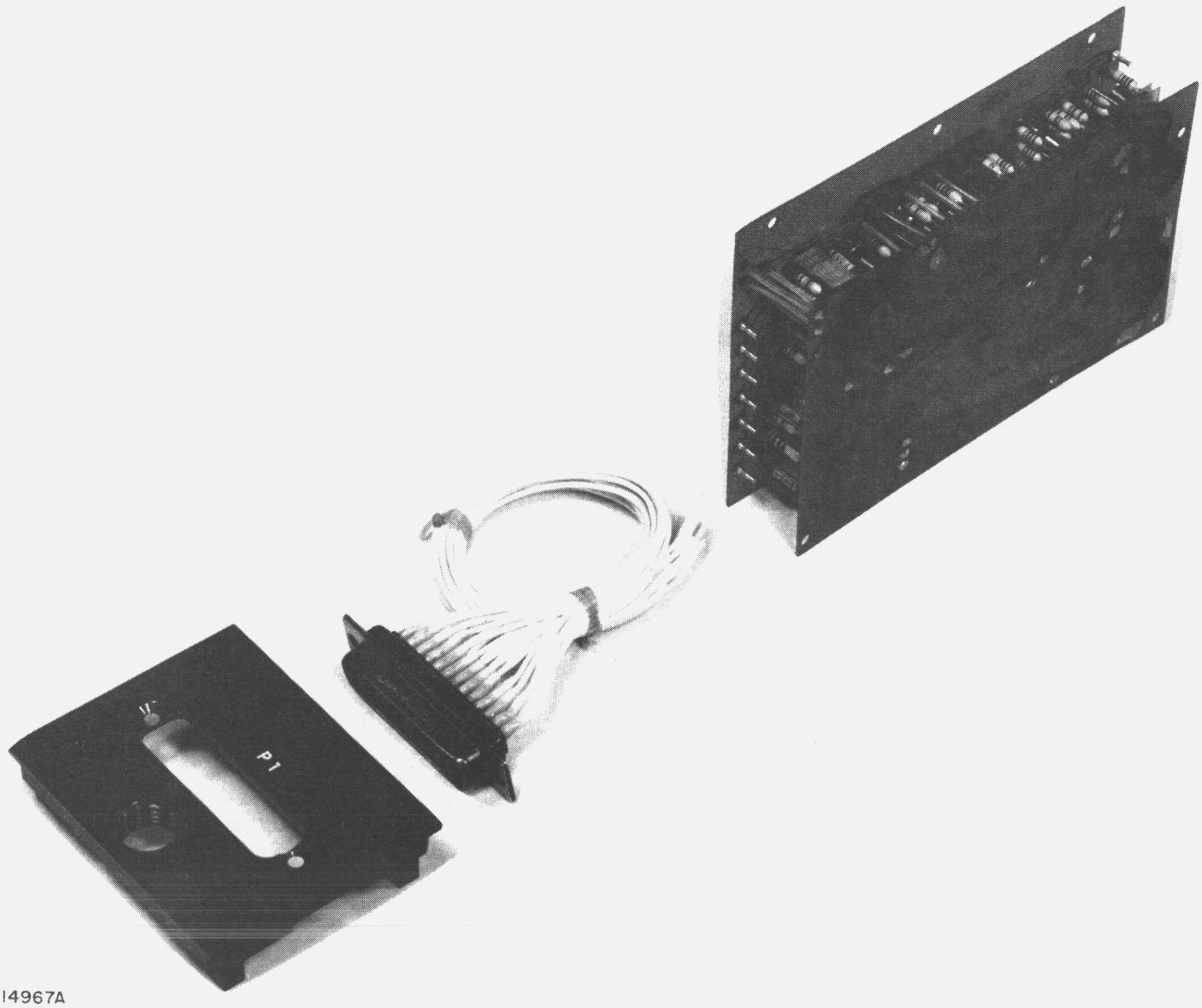

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Figure 5 POWER AND SIGNAL CONDITIONER MODULE

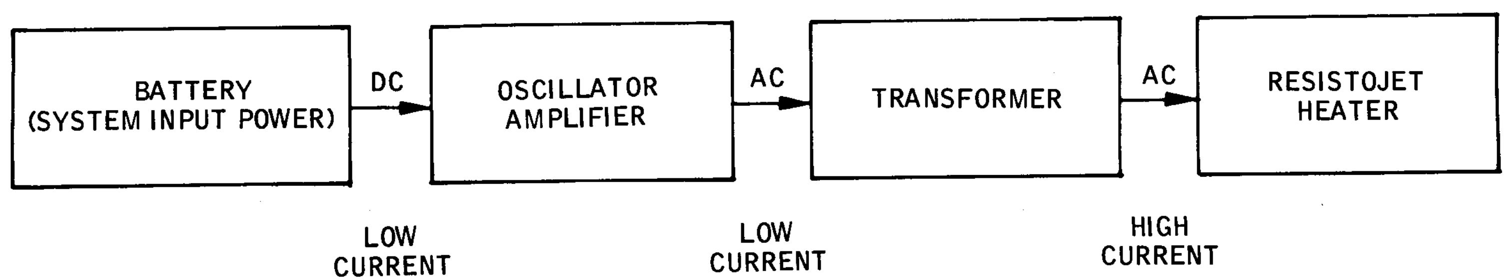

Figure 6 POWER SUPPLY SCHEMATIC FOR THE RESISTOJET HEATER ELEMENTS

4. Station-Keeping Module

The station-keeping package contains the necessary circuitry to supply power to the station-keeping module. The station-keeping module is identical to the power and signal conditioning module with the exception of the command control function. The station-keeping function is intended to operate on command only. A schematic diagram of the telemetry and control functions of the station-keeping module is shown in Figure 7.

As in the case of the power and signal conditioning package there are a total of seven output channels.

The model specifications for the station-keeping package are presented in Appendix C of reference 2.

5. Propellant Storage Signal Conditioner Module

The propellant storage signal conditioner, shown in Figure 8, energizes without command control the propellant pressure regulation valves/pressure switches and conditions power for three pressure transducers and a thermistor-circuit. The module also conditions the three pressure transducer signals, the thermistor signal, and the primary pressure regulation valve voltage signal.

6. Three-Axis Sensor and Light Source

The light source consists of an incandescent lamp, a condensing lens assembly, an illuminated aperture, and a projection lens that has its principal focal point at the illuminated circular aperture.

The sensor consists of a highly corrected lens that receives the beam of light from the light source and focuses an image of the illuminated aperture in the light source onto a quadrant of silicon light-sensitive cells. Angular motions of the sensor, with respect to the light source, result in a displacement of the circular image on the quadrant of cells. Each quadrant of the cell assembly is filled with a polarization analyzer to allow rotation about the optic axis to be sensed. The outputs of the cells are in turn fed to groups of solid-state amplifiers in a logic circuit that permits the angular deviation of each axis to be separated.

A more complete description of operation of these items may be found in reference 2.

C. PROPELLANT STORAGE AND FEED SYSTEM

The basic zero-gravity propellant feed and storage system is shown in Figure 9. A photograph of the system is shown in Figure 10.

Referring to Figure 9, the zero-gravity propellant feed system consists of an ammonia storage tank in which ammonia is stored in both the gaseous and liquid state. The valves, V_1 and V_2, are opened when the pressure in the preplenum falls below the pressure setting on the pressure switches, PS_1 and PS_2. One pressure switch is set slightly below the other pressure switch. Thus, if one valve fails closed, the other will then open. A principal feature of the design is the inclusion of a preplenum chamber and orifice which are located immediately upstream of the main plenum chamber. By suitably adjusting the orifice diameter and size of the preplenum, it is possible to hold the plenum pressure to + 1 percent pressure variation with either gas or liquid flowing into the preplenum. The zero-gravity propellant pressure regulation and feed system concept was partially developed under Contract NAS3-5908 (reference 5) and was subsequently utilized in resistojet experimental engines flown on two of the ATS satellites.

The critical components in the zero-gravity ammonia propellant feed system are shown in Table III.

TABLE III

CRITICAL COMPONENTS IN THE ZERO-GRAVITY AMMONIA PROPELLANT FEED SYSTEM

Component	Manufacturer
Flow Control Valves, V_1 and V_2	Carleton Valve No. 1809-001-35
Pressure Switches, PS_1 and PS_2	Bristol Co. Pressure Switch No. C2069-1
Pressure Transducers, PT_2 and PT_3 (0 to 20 psia, 0 to 75 psia)	Micro-Systems Pressure Transducer Model No. 1003-0151-100
Pressure Transducer, PT_1 (0 to 300 psia)	Micro-Systems Pressure Transducer Model No. 1003-0151-300

A critical problem in the development of the feed system has been to obtain reliable operation of valves V_1 and V_2 when they are directly subjected to liquid ammonia. This difficulty has been overcome by using an elastomer material developed by Avco that has shown excellent compabibility with the liquid ammonia.

Performance tests with the system have demonstrated ± 1 percent pressure regulation for a thrustor flow rate of 2.5×10^{-4} pound/sec for periods of over 200 seconds. Regulation control has also been demonstrated for flow rates of 5.0×10^{-5} pound/sec for a single pulse of 0.015 second duration. Regulation system characterization data is given in Appendix A.

The stainless steel, liquid ammonia storage tank has a capacity of 2796 cubic inches, which will store 56 pounds of ammonia. Tank ullage, when fueled with 56 pounds of ammonia, is approximately 2 percent at 120°F. The tankage was designed for a burst pressure of 1200 psi and was proof tested at 450 psi.

The system fueling procedure and equipment are described in Appendix B.

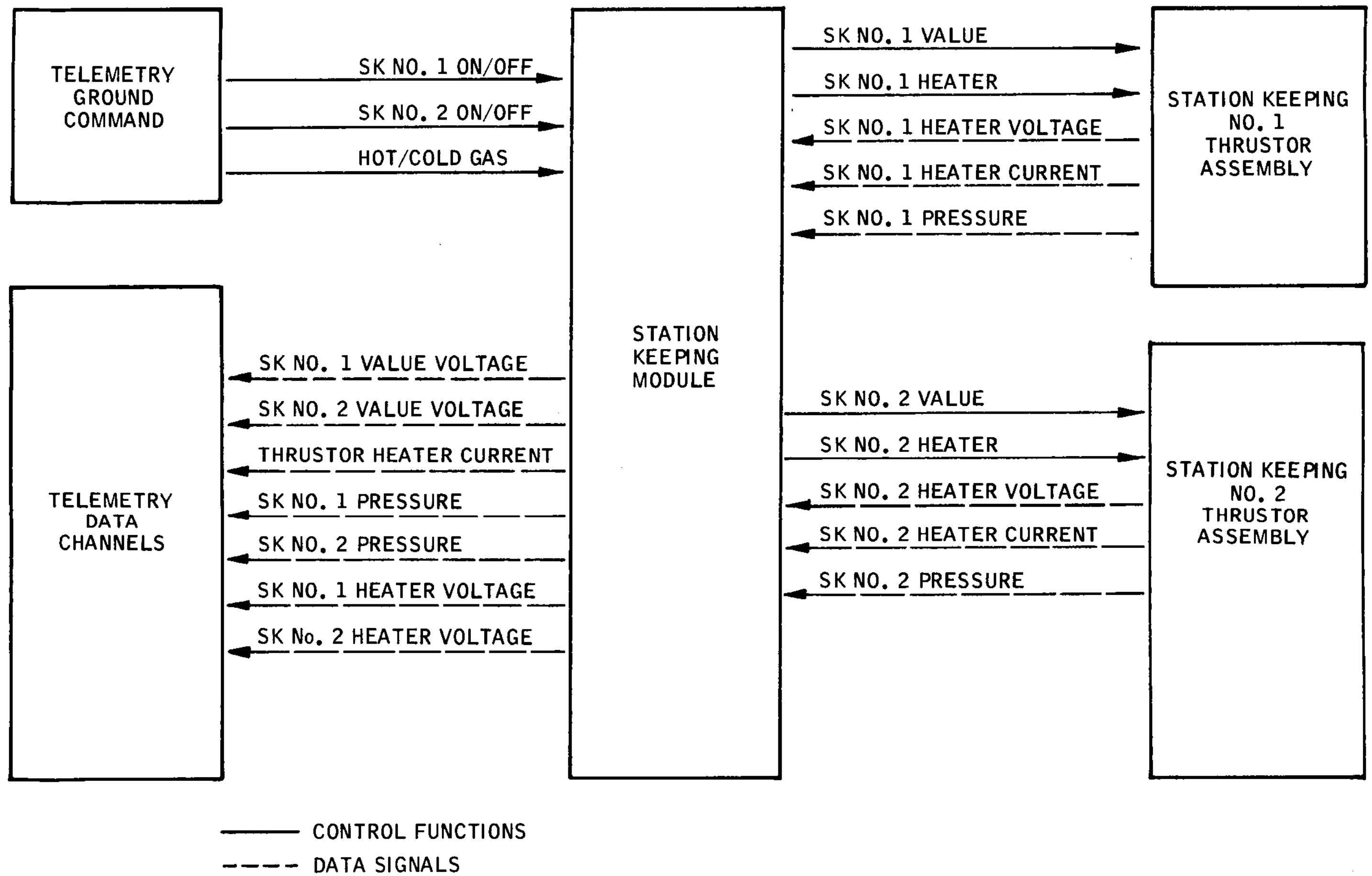

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Figure 7 SCHEMATIC DIAGRAM OF TELEMETRY AND CONTROL FUNCTIONS WITH THE STATION-KEEPING MODULE

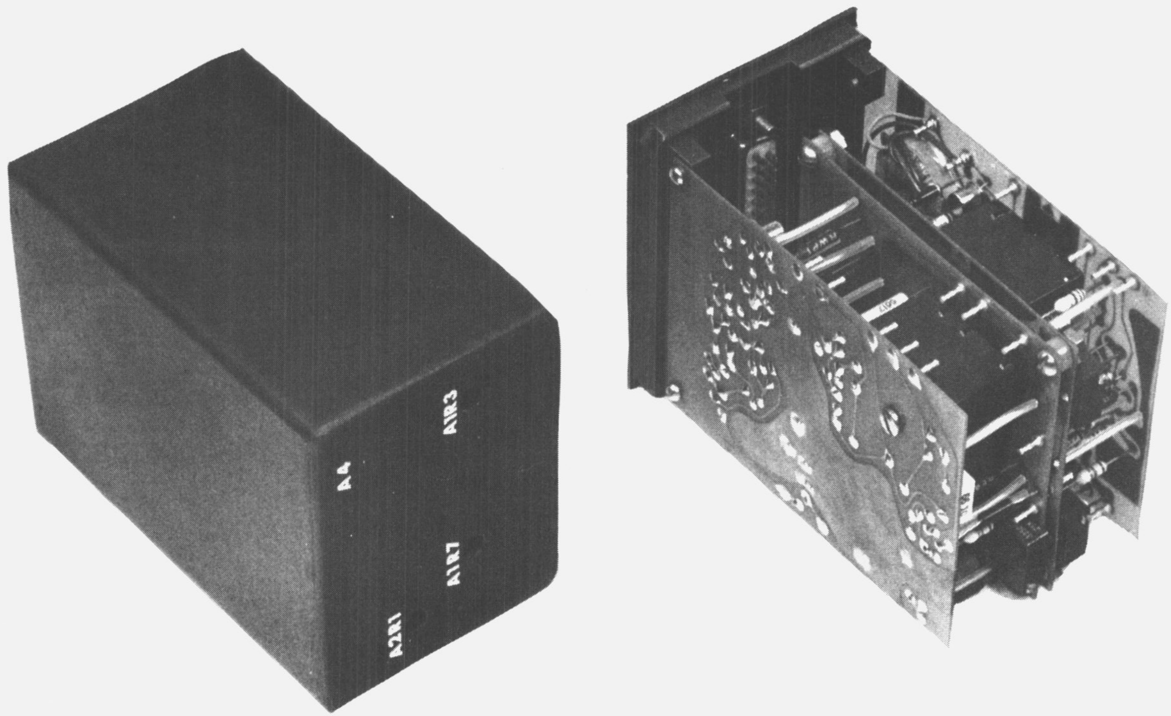

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Figure 8 PROPELLANT STORAGE SIGNAL CONDITIONER MODULE

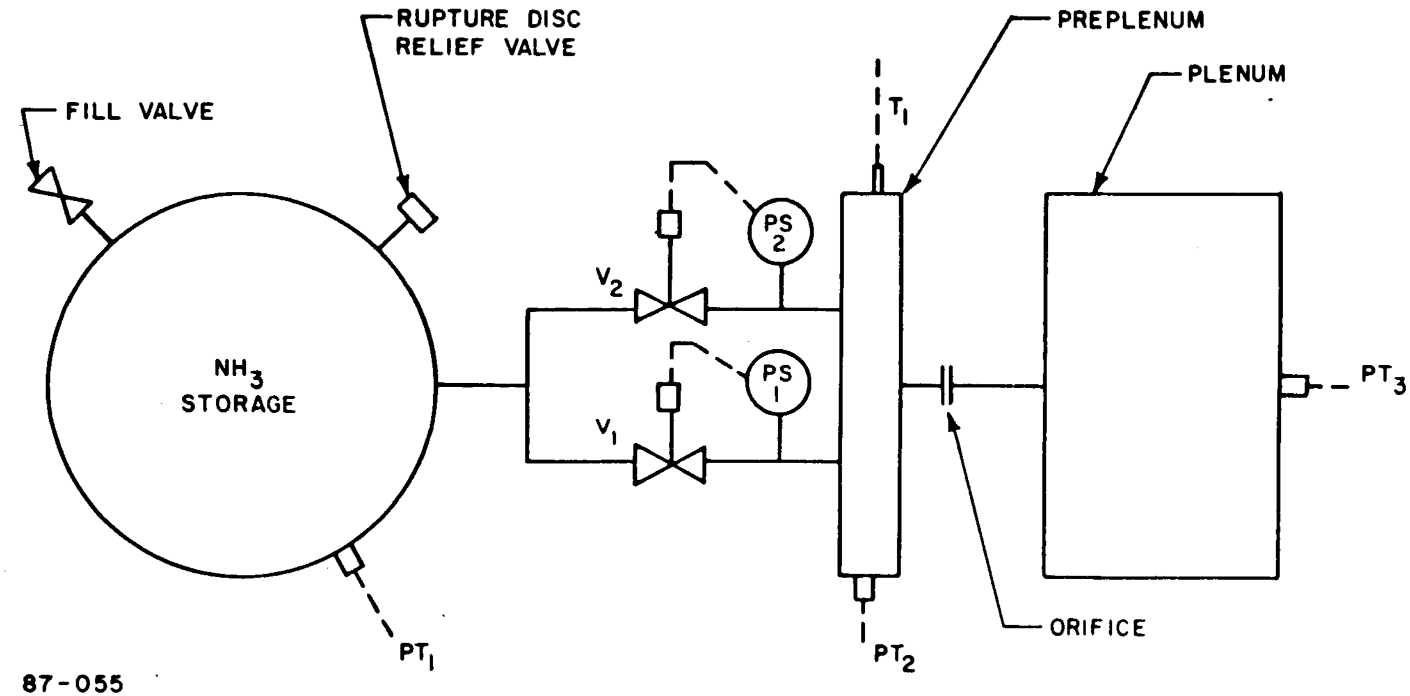

Figure 9 SCHEMATIC OF THE AMMONIA STORAGE AND FEED SYSTEM

Figure 10 AMMONIA STORAGE AND FEED SYSTEM

D. THRUSTOR ASSEMBLY

The basic resistojet thrustor design used in the three-axis system is the fast heat-up resistojet which has been described previously, reference 2, and is shown in Figure 11. The thrustor assembly consists of a solenoid valve (Carlton Valve No. 1809-001), a pressure transducer (Micro-Systems Model No. 1003-0151), a combined fast heat-up heater and exit nozzle, a thrustor heater transformer, and an assembly mount.

The fast heat-up thrustor heater tubes were fabricated by vapor-deposition of rhenium on premachined materials. After removal of the mandrel, the tube and a stainless steel nozzle are nioro brazed together at the nozzle entrance. A photograph of a thrustor is shown in Figure 12. Table IV presents a thrust and specific impulse characterization of the thrustors delivered with the system. Each data point presented in the table represents the average of at least three test runs. The detailed method for measurement of thrust is given in QATP SD-107, reference 3, Data Log. It is noted from the data that there is less than 10 percent variance in thrustor specific impulse. Differences of thrust reflect effects caused by extremely small variances between thrustors. For flight applications, thrustors would be characterized and then matched.

One thrustor, serial number F720419, was tested and characterized over a wide range of input current, nozzle box pressure, and preflow warm-up time. The steady state thrust measurements versus thrustor power and nozzle box pressure are given in Figure 13. Propellant mass flow versus thrustor power and pressure is shown in Figure 14, and specific impulse in Figure 15. The effect of the preflow warm-up (power-on) parameter is given in Table V.

Four thrustors were life-tested, two according to a mode typical of attitude control and two in a mode representative of station-keeping. The two attitude control thrustors were operated for over 101,000 cycles.

Each attitude control cycle consisted of a heater warm-up of four seconds with heater power and no flow, two seconds of gaseous ammonia flow with 5 watts of power, a cool-down period of eight seconds with flow on and heater power off, followed by a one second period with flow and heat off. Nozzle box pressure during the tests was 5.8 psia. The tests representative of the station-keeping application consisted of over 300 cycles, with a cycle being defined as a four second preheat with heater power and no flow; 30 minutes with gaseous ammonia flow, a nozzle box pressure of 5.8 psia, and 5 watts of power; a cool-down period of 8 seconds with flow on and heater power off; followed by a 1 second period with both flow and heat off. Two thrustors were tested in this mode. Both life tests were conducted in an evacuated bell-jar facility at a pressure of less than 10^{-3} torr.

Photographs of the life cycled nozzle throats are shown in Figures 16 and 17. The attitude control thrustors are essentially unchanged, while the station-keeping thrustors show damage to the stainless steel nozzle throats. Subsequent to the fabrication of the thrustors for this program, a new thrustor has been fabricated using a vapor deposited rhenium nozzle in place of the stainless steel nozzle. Tests with this nozzle indicate no measurable amount of throat degradation. No apparent degradation of the rhenium heater tube has ever been observed.

As a part of this program, several thrustors and nozzles were fabricated and tested to establish thrustor and nozzle geometry effects on performance. The results from the research are presented in Appendix C.

Though there was no requirement to establish the thrustor thrust vector, a method was developed that could determine this vector to ± 1/4 of a degree in both planes. This measurement would be required whenever thrustors are installed on a spacecraft. The technique and the measurement results with four thrustors tested are given in Appendix D.

The thrustor heater power transformer is located in close proximity to the thrustor to minimize power lead losses. The heater power circuit for either the attitude control or station-keeping thrustor assemblies is described in Section II.B.3.

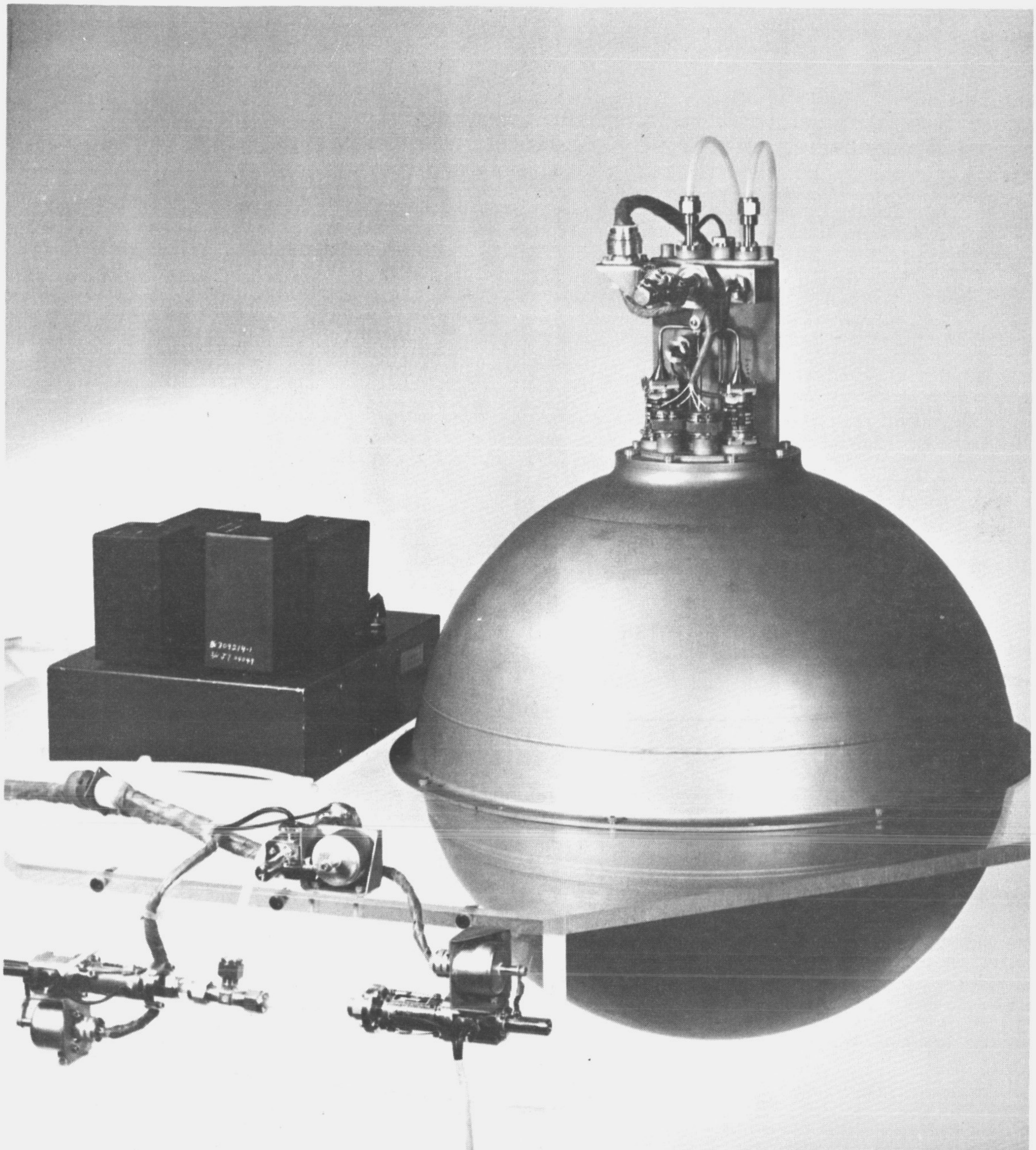

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Figure 11 THREE THRUSTOR ASSEMBLIES SHOWN WITH PROPELLANT STORAGE AND FEED SYSTEM, AND SYSTEM ELECTRONICS

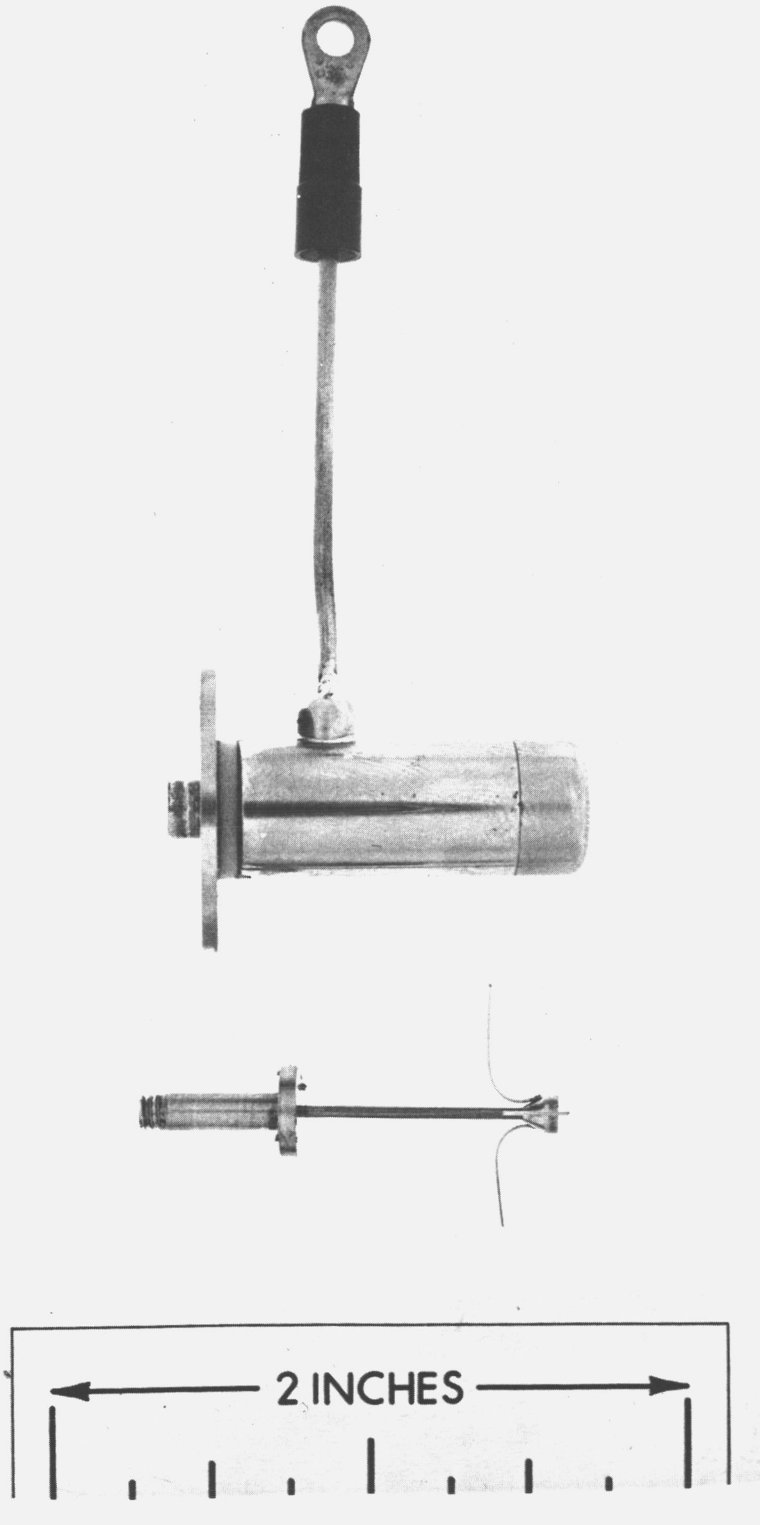

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Figure 12 RHENIUM THRUSTOR

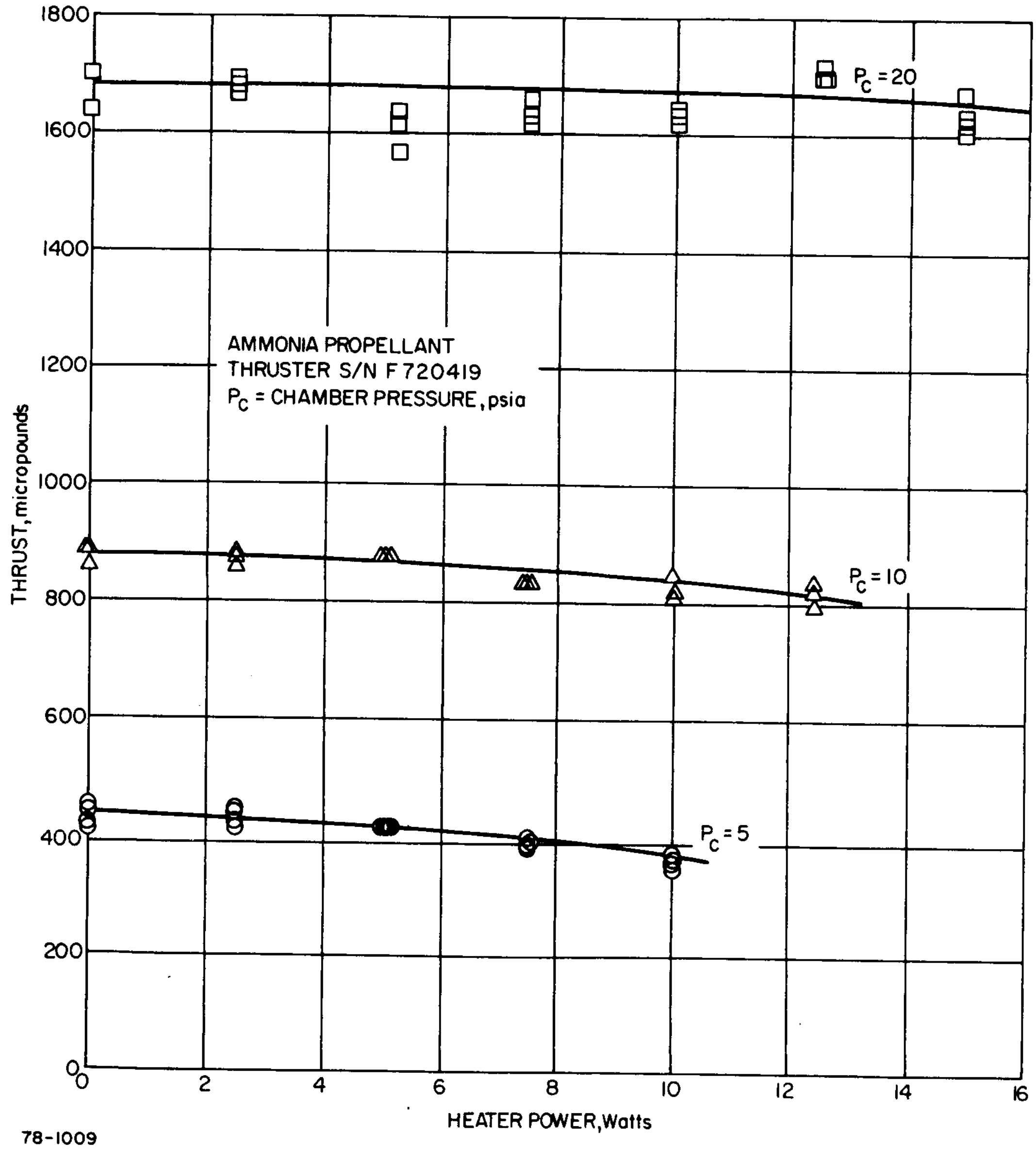


Figure 13 THRUSTOR PERFORMANCE: THRUST VERSUS POWER

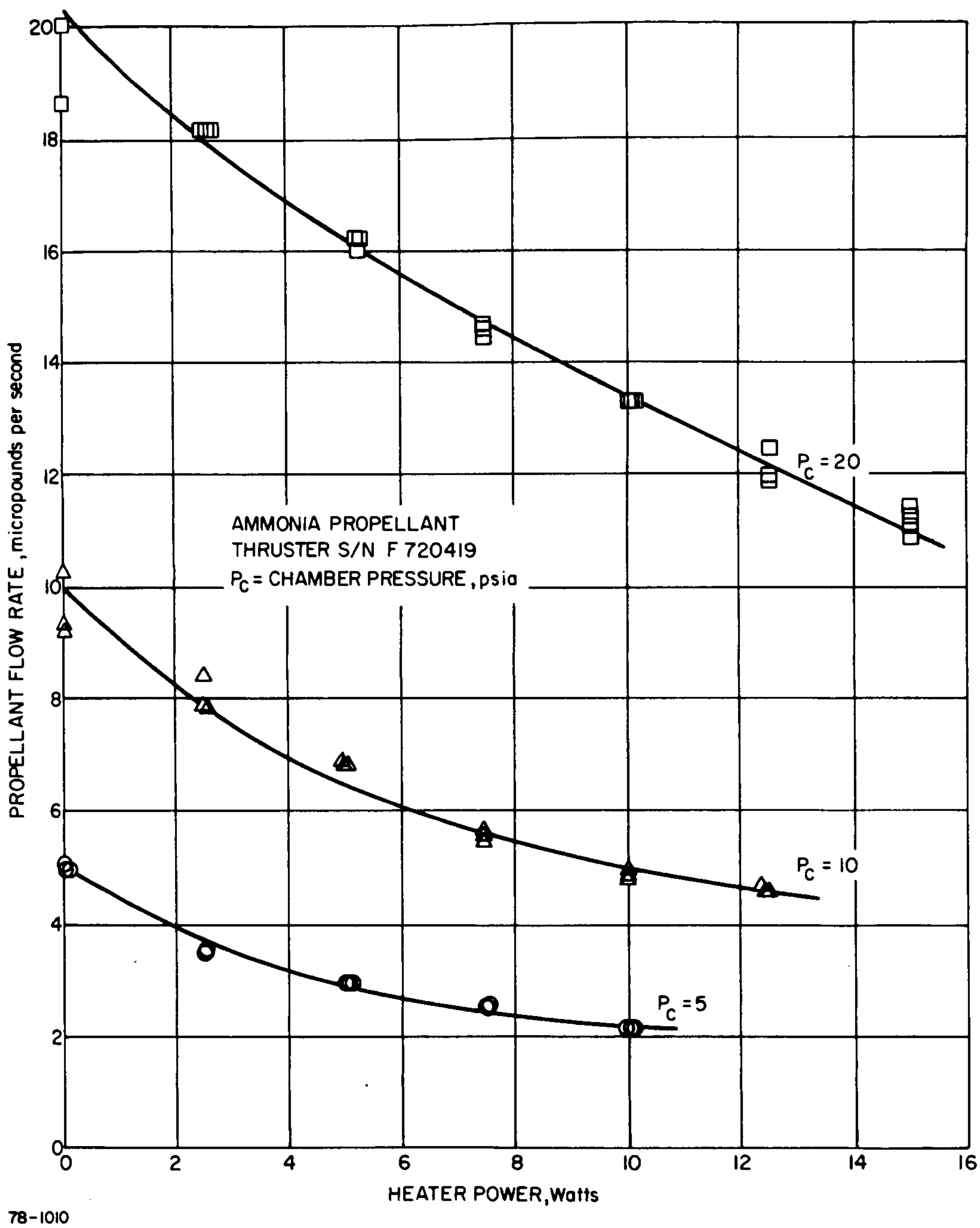


Figure 14 THRUSTOR PERFORMANCE: FLOW RATE VERSUS POWER

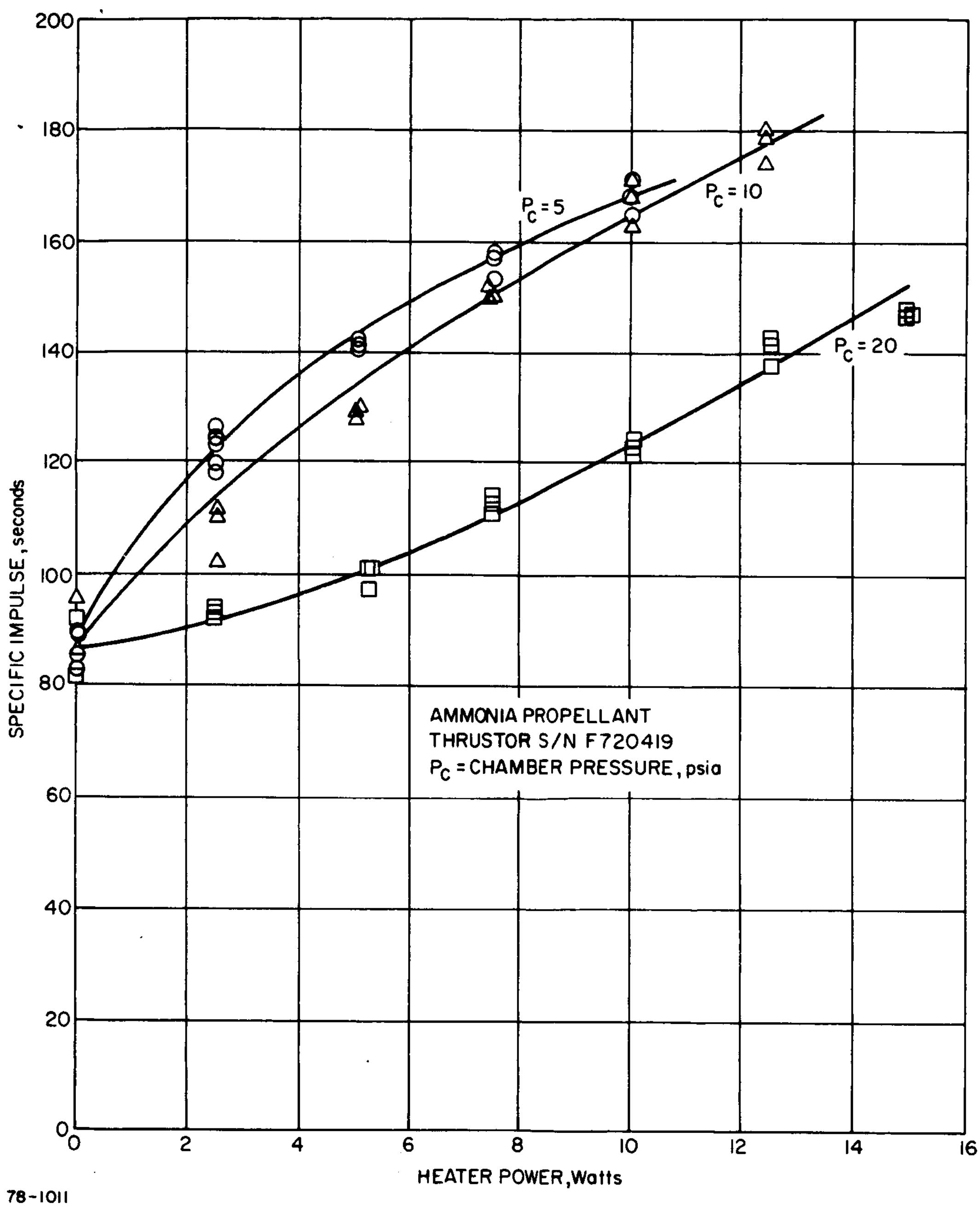
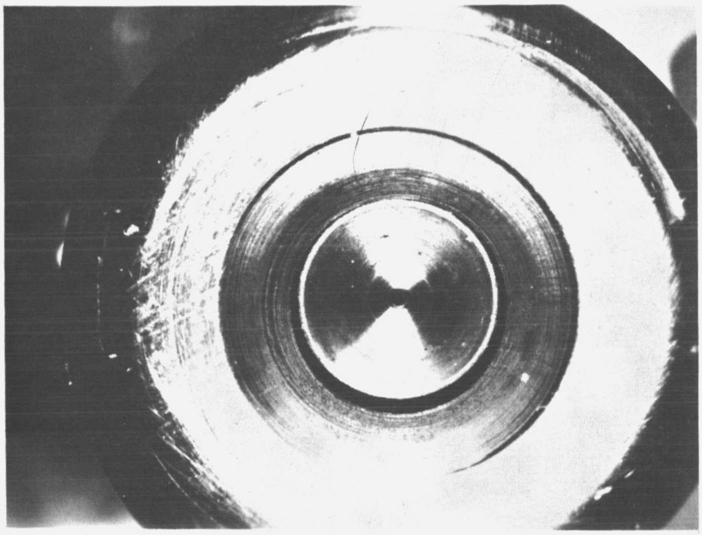


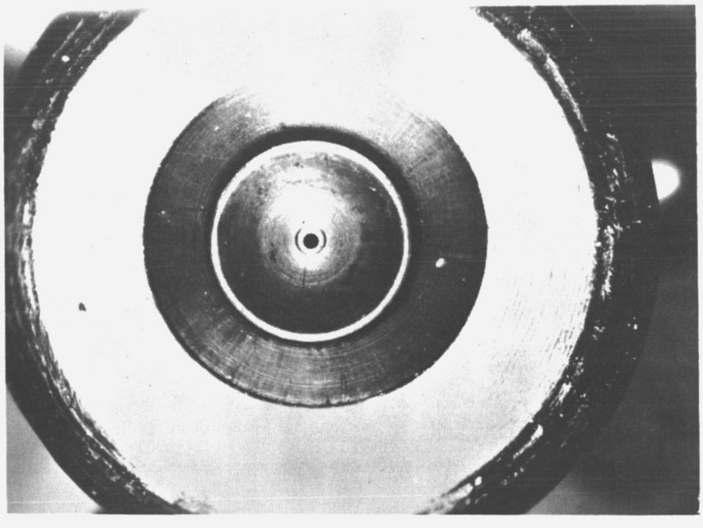
Figure 15 THRUSTOR PERFORMANCE: PERFORMANCE VERSUS POWER



ATTITUDE CONTROL
STAINLESS STEEL
5 WATTS
101,000 CYCLES
HEATING PERIOD 2 SEC.

THRUSTOR a.
PLATE 4611B

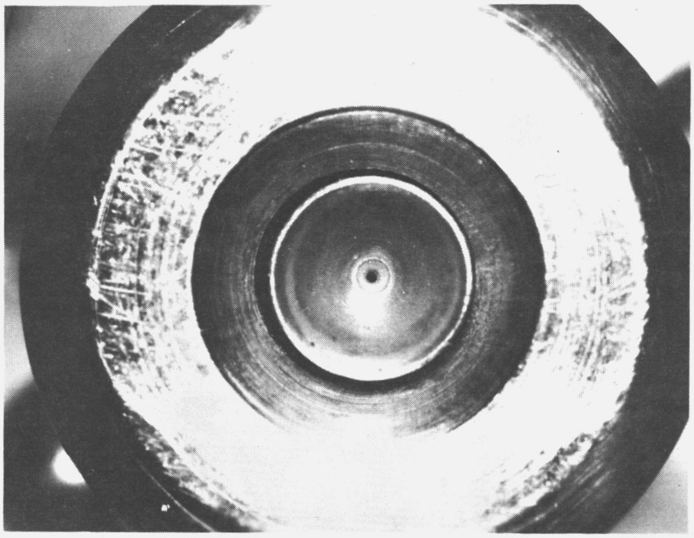
10X



THRUSTOR b.
PLATE 4611C

10X

Figure 16 NOZZLE OF LIFE CYCLED ATTITUDE CONTROL THRUSTORS



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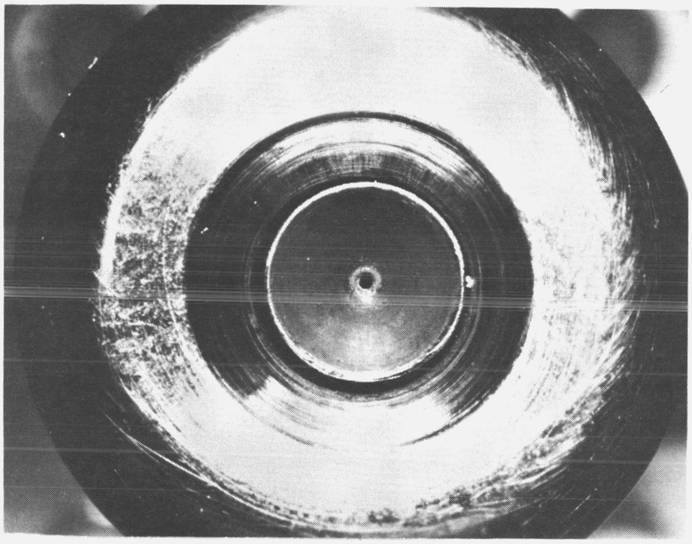
STATION KEEPING
STAINLESS STEEL
5 WATTS
300 CYCLES
HEATING PERIOD
30 MINUTES

THRUSTOR C.
PLATE 4611



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THRUSTOR d.
PLATE 4611A

Figure 17 NOZZLES OF LIFE CYCLED STATION-KEEPING THRUSTORS

78-1013

TABLE IV

THRUSTOR CHARACTERIZATION DATA

Thrustor Serial No.	Nozzle Box Pressure (psia)	Power to Heater Tube (watts)	Thrust (lb)	Specific Impulse (seconds)
H726634	4.6	0	433	81
H726634	4.8	6.6	419	146
H726628	4.3	0	373	82
H726628	4.6	6.9	319	137
H726632	4.4	0	376	86
H726632	4.6	6.5	314	137
H726630	4.2	0	322	79
H726630	4.3	6.0	286	132
H726630	4.6	6.7	303	136
H726638	4.0	0	341	81
H726638	4.2	6.9	324	150
H726637	4.0	0	349	82
H726637	4.5	6.8	383	142
H726635	4.2	0	305	76
H726635	4.5	6.7	327	138
H726633	4.4	0	333	78
H726633	4.5	6.7	306	145
H726639	4.7	0	388	90
H726639	4.7	7.1	325	155
H726629	4.7	0	427	89
H726629	4.7	6.5	387	144
H726631	4.7	0	348	82
H726631	4.8	6.8	351	138
H726636	4.7	0	363	81
H726636	4.7	6.9	312	146

TABLE V

EFFECT OF PREFLOW WARM-UP TIME ON THRUSTOR PERFORMANCE

Pc Thrustor Nozzle Box Pressure (psia)	P Heater Power Dissipation (watts)	τ Heater Pre-Heat Time (seconds)	T Time to Reach 95% of Steady-State I_{sp} (sec)
5.1	2.5	1	27
		3	26
		5	21
		10	22
		15	1
	5.0	1	26
		5	20
		10	13
	7.5	1	20
		5	15
		10	11
	10.0	1	15
		5	13
		10	7
10.2	2.5	1	18
		5	11
		10	1
	5.0	1	11
		5	13
		10	5
	7.5	1	17
		5	12
		10	1
	10.0	1	16
		5	10
		10	1
	12.4	1	13
		5	6
		10	2
20.0	2.5	1	2
		5	1
		10	1
	5.2	1	10
		5	4
		10	2
	7.5	1	9
		5	2
		10	3
	10.0	1	8
		5	3
		10	3
	12.5	1	8
		5	4
		10	3
	14.9	1	9
		5	1
		10	3

III. COMPONENTS AND SUBSYSTEMS

A. INTRODUCTION

All system components and subsystems are serialized for identification and control. Formal Quality Assurance Test Procedures have been written and used on this program, for nearly all components and subsystems. A list of the assemblies and the results from the QATP tests for the components and subsystems are presented in this section.

B. ASSEMBLY AND TEST

1. Assembled Subsystems

One complete propellant storage and feed system was assembled, tested, and delivered. The following components were in the assembly:

Propellant Storage and Feed System 309360-1 S/N G704622

Pressure Switch	C2069-2		S/N E725259
Pressure Switch	C2069-3		S/N E700096
Refief Valve	1962001-7		S/N G700025
Fill Valve	1176-1		S/N G720258
Pressure Transducer	1003-0151	(0-20 psi)	S/N J702328
Pressure Transducer	1003-0151	(0-50 psi)	S/N J702324
Pressure Transducer	1003-0151	(0-300 psi)	S/N J702326
Thermistor K816			S/N F726869
Connector DSM00-12-14P			S/N G700022
Valve Assembly (Regulator)	309394-1		S/N G704700
Solenoid Valve	1809-001-41		S/N G700015
Solenoid Valve	1809-001-41		S/N G700014

One spare regulation system mount and plenum tank (309362-1), S/N N626030, was delivered.

Thrustor Mount Assembly Number 1, 309366-1, S/N G704617

Solenoid Valve	1809-001-20	S/N G700220
Pressure Transducer	1003-0151	S/N J702337
Thrustor Assembly	309370-1	S/N H726631
Transformer	100301-5	S/N J702006

Thrustor Mount Assembly Number 2, 309366-1, S/N G704618

Solenoid Valve	1809-001-20	S/N G700217
Pressure Transducer	1003-0151	S/N J702327
Thrustor Assembly	309370-1	S/N H726628
Transformer	100301-5	S/N J703008

Thrustor Mount Assembly Number 4, 309366-1, S/N G704620

Solenoid Valve 1809-001-20	S/N G700217
Pressure Transducer 1003-0151	S/N J702325
Thrustor Assembly 309370-1	S/N H726636
Transformer 100301-5	S/N J703009

Eight (8) additional thrustor assemblies were completed and delivered.

The following electronics were assembled and delivered:

a. Five Logic Modules, 309214-1:

S/N J704049
S/N F704946
S/N F705207
S/N F704059
S/N J701008

(One additional unit was assembled, S/N G709050, but not delivered.)

b. Two Station-Keeping Modules, 309301-1, S/N J804053 and S/N J701010

(One additional unit was assembled but not delivered.)

c. Five Power Signal Conditioners, 309180-1:

S/N J704055
S/N J701007
S/N F704930
S/N J701012
S/N G709047

(One additional unit was assembled, G709052, but not delivered.)

d. Two Supply Conditioners, 30922901, S/N J704053 and S/N J704941

(One additional unit was assembled, but not delivered.)

e. Three Junction Boxes, 309121-1 (No Serial Numbers)

f. Three Adjustment Boxes (Drawing Not Released) (No Serial Numbers)

(One additional unit was assembled but not delivered.)

2. Component and Subsystem Test

A Quality Assurance Test Procedure was prepared for each component and subsystem whenever it was feasible that the performance and operational characteristics of the item could be determined by a formalized test. Accordingly, QATP's have been prepared and used for each electronic module, valve, pressure switch, pressure transducer, and thermistor. It has been found that a formalized procedure is not applicable except as a general guide when the test to be performed is somewhat developmental, as with the thrustors or propellant pressure regulator subsystem. A listing of the QATP's used on the program is found in Appendix E. The completed QATP's are in the Data Log, reference 3. A satisfactory completion of a QATP is required for the item to be acceptable for flight usage. A complete analysis program was set up to review QATP data to establish component or subsystem acceptability. The results of this analysis, typical for component evaluation, are given for two of the pressure transducers in the Data Log, reference 3, at the end of Section II.

All of the electronic modules, pressure switches, pressure transducers, burst-disc relief valves, thermistors, and the Carleton valves had acceptable quality assurance tests. The Valcor valves were used to replace some of the Carleton Controls flow valves for the purpose of engineering tests and therefore were not tested by a formalized QATP. It was observed that there are two pressure transducer problems. The transducers tend to show high sensitivity, which is desirable for measurement accuracy, but causes range reduction when the transducer is operated with the electronics power and signal conditioning. Due to this condition, the transducer may indicate saturation at pressures of interest. The second problem is that the transducers show temperature zero shifts. Therefore, whenever the thermal environment changes, the zero reference must be checked.

Thrustor characterization is reported in Section II.D in this report. The propellant pressure regulation characterization is found in Section II.C and Appendix A.

Subsequent solenoid valve tests have shown the Carleton valve in its present configuration to be acceptable for flight usage.

IV. SYSTEM CALIBRATION, PERFORMANCE, AND QUALIFICATION

A. INTRODUCTION

One complete single axis system, consisting of a logic module, a supply conditioner, a power and signal conditioner, a station-keeping module, a propellant storage and feed system, and four thrustor assemblies, was assembled for performance and flight qualification testing. A formal Systems Test Procedure, Qualification Test Plan STP SSD-1011, was prepared to control and document this evaluation. Three additional Systems Test Procedures were written to characterize system performance and operation: Atmosphere Long Form Test, STP SSD-1012; Vacuum Long Form Test, STP SSD-1013; and Systems Performance Test, STP SSD-1014. The completed STP's are filed in the Data Log, reference 3.

B. SYSTEM CALIBRATION

Following system assembly (See Figure 18), all of the instrumentation sensors were calibrated through their associated electronic modules (see Section II). System calibration procedure and data are given in Appendix F.

C. PRELIMINARY OPERATIONAL TEST

Prior to the start of the System Qualification Test, a preliminary system operational test was run during which the electronics and the regulation and feed system, two attitude control thrustor assemblies, and two station-keeping thrustor assemblies were operated as a system in atmosphere. In lieu of the thrustors (thrustors are damaged if operated hot in the atmosphere), 0.05 ohm resistors were placed across the thrustor heater transformers. The object of this test was to establish if the system would go from mode to mode without difficulty, and that all telemetry channels were functioning normally. Due to the high gains of the plenum, preplenum, and nozzle box pressure transducers, all low pressure telemetry channels were saturated. However, in vacuum operation the outputs of these channels are mid-range. The 14.7 psi differential due to atmosphere operation is sufficient to saturate all of the low pressure telemetry channels.

The sequence of commands issued is given in Table VI and the telemetry data for the nine basic modes is presented in Table VII. This data provided the basic set of expected values for hot and cold manual operation (except for the saturated pressure channels). The automatic attitude control mode was balanced and the input signal shorted, thus assuring that when the system was in the automatic mode, the attitude control thrustors would not be turned on. The actual "hot" telemetry values of heater current and voltage are somewhat different from those in Table VII, because the thrustor heater tubes are not exactly 0.05 ohm; however, the data provides a good approximation of the actual value.

The results of the operational tests indicated that no difficulty was encountered in going from mode to mode. There was no interference between the station-keeping commands and attitude control operations, and vice-versa.

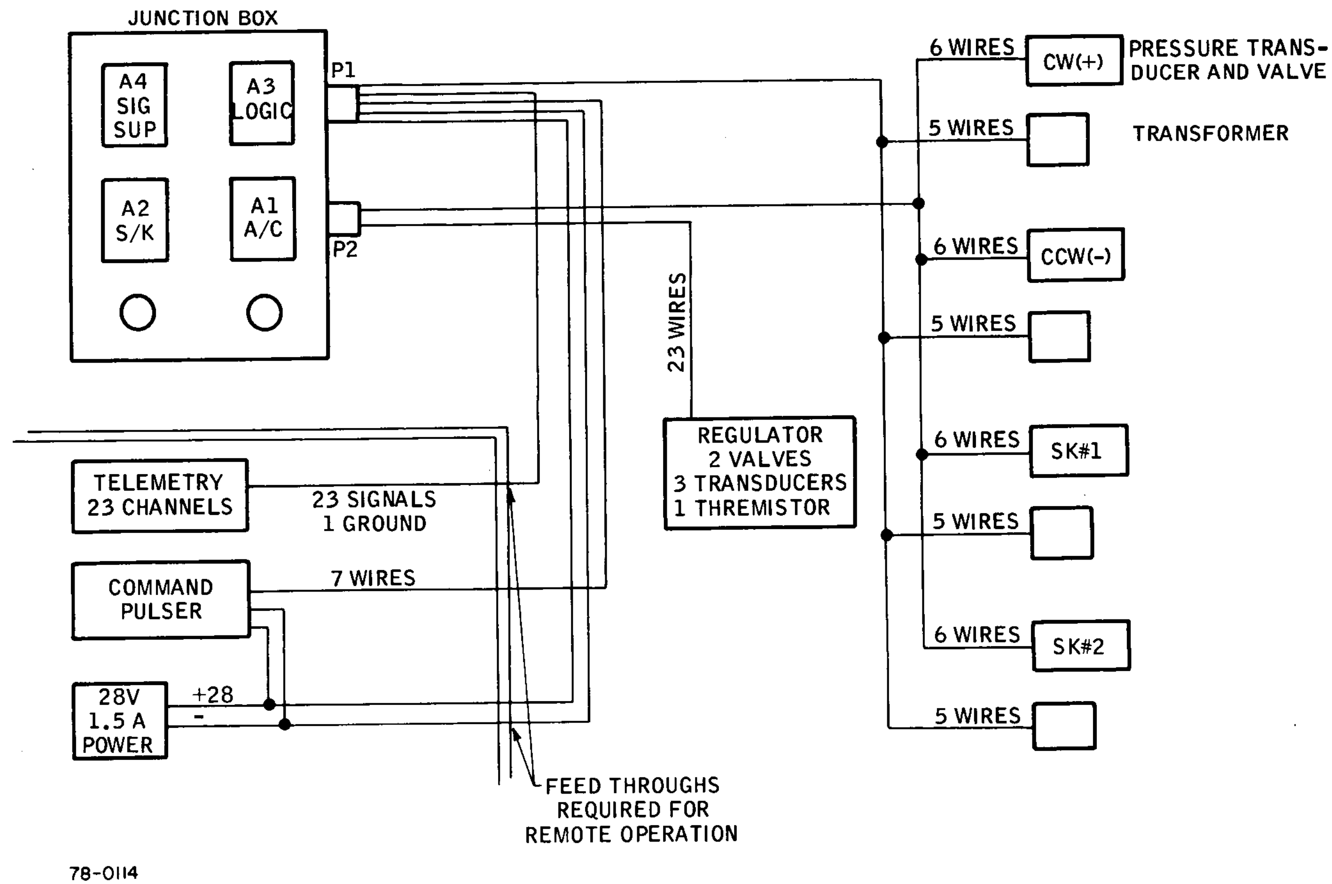

Figure 18 SINGLE-AXIS SYSTEM BLOCK WIRING DIAGRAM

TABLE VI

SEQUENCE OF COMMANDS

1. Power ON *	23. Attitude Control Cold/Hot
2. Attitude Control Cold/Hot	24. CCW ON
3. CW ON *	25. Auto
4. Attitude Control Hot/Cold*	26. CW ON
5. Attitude Control Cold/Hot	27. Auto
6. CCW ON *	28. Station-Keeping Cold/Hot
7. Attitude Control Hot/Cold *	29. No. 1 Station-Keeping ON *
8. CW ON	30. Station-Keeping Hot/Cold *
9. Attitude Control Cold/Hot	31. Station-Keeping Cold/Hot
10. CCW ON	32. No. 2 Station-Keeping ON *
11. CCW OFF	33. Station-Keeping Hot/Cold *
12. CW ON	34. No. 1 Station-Keeping ON
13. CW OFF	35. Station-Keeping Cold/Hot
14. CCW ON	36. No. 2 Station-Keeping ON
15. Attitude Control Hot/Cold	37. No. 2 Station-Keeping OFF
16. CCW OFF	38. No. 1 Station-Keeping ON
17. CW ON	39. No. 1 Station-Keeping OFF
18. CW OFF	40. Station-Keeping Hot/Cold
19. CCW ON	41. No. 2 Station-Keeping ON
20. Auto	42. No. 2 Station-Keeping OFF
21. CW ON	43. No. 1 Station-Keeping ON
22. Auto	44. No. 1 Station-Keeping OFF

*Modes given in Table VII.

TABLE VII

TELEMETRY OUTPUTS

Function	Switch	Telemetry Output Volts								
		Power ON	CW (+) Cold	CW (+) Hot	CCW (-) Cold	CCW (-) Hot	No 1 (+) Cold	No 1 (+) Hot	No 2 (-) Cold	No 2 (-) Hot
Supply P	1A	0.80	0.80	0.79	0.79	0.78	1.14[3]	1.14	1.22	1.23
Preplenum P	2A	5.16	5.15	5.15	5.15	5.15	5.15	5.15	5.15	5.15
Plenum P	3A	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27
Reg Valve	4A	0.0	0.0/2.52	0.0/2.50	0.0/2.51	0.0/2.50	0.0/2.47	Pulse	Pulse	Pulse
Thermistor	5A	3.73	3.75	3.76	3.79	3.77	3.80	3.73	3.83	3.84
A/C Heater I	6A	0.0	0.0	3.06	0.0	2.83	0.0	0.0	0.0	0.0
CW (+) Volts	7A	0.0	0.0	3.19	0.0	0.41	0.0	0.0	0.0	0.0
CW (+) NBPT[1]	8A	5.17	5.18	5.18	5.17	5.17	5.18	5.17	5.17	5.17
CW (+) Valve	9A	0.0	2.38	2.37	0.0	0.0	0.0	0.0	0.0	0.0
CCW (-) Volts	10A	0.0	0.0	0.40	0.0	2.90	0.0	0.0	0.0	0.0
CCW (-) NBPT	11A	5.15	5.15	5.15	5.15	5.15	5.15	5.15	5.15	5.15
CCW (-) Valve	12A	0.0	0.0	0.0	2.41	2.46	0.0	0.0	0.0	0.0
S/K Heater I	1B	0.0	0.0	0.0	0.0	0.0	0.0	2.71	0.0	2.82
No 1 (+) Volts	2B	0.0	0.0	0.0	0.0	0.0	0.0	3.01	0.0	0.40
No 1 (+) NBPT	3B	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14
No 1 (+) Valve	4B	0.0	0.0	0.0	0.0	0.0	2.43	2.43	0.0	0.01
No 2 (-) Volts	5B	0.0	0.0	0.0	0.0	0.0	0.0	0.39	0.0	3.10
No 2 (-) NBPT	6B	5.03	5.03	5.03	5.03	5.03	5.03	5.03	5.03	5.03
No 2 (-) Valve	7B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.42	2.41
System I	8B	1.90	2.03/1.97[2]	2.76/2.82	1.94/2.00	2.70/2.76	1.92/1.98	2.74 Pulse	1.96 Pulse	2.77 Pulse
$\theta + \dot{\theta}$ (out)	9B	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$\theta + \dot{\theta}$ (TLM)	10B	2.47	2.47	2.47	2.47	2.47	2.48	2.48	2.48	2.48
θ	11B	2.38	2.38	2.38	2.38	2.38	2.38	2.39	2.39	2.39

[1]NBPT: Nozzle box pressure transducer.
[2]2.03/1.97 means valves were pulsing between values indicated.
[3]The supply was fueled between CW hot and No 1 cold.

The state of the system was monitored after each command to ascertain if the system was in the proper mode and that the readouts were the same as the previous value. During the course of the testing there never was a deviation from value to value of more than 2 percent from one set of readouts and a subsequent set of the same mode.

D. SYSTEM QUALIFICATION

1. Test Description and Specifications

The Qualification Test was written so that if the system completed the test satisfactorily, there would be assurance that the system would be able to perform its function of satellite control within the limits of the hypothetical mission defined in the contract Statement of Work. A complete single-axis system (representative of each component and subsystem developed) was tested in accordance with this plan. The environments included in the test are qualification levels and the simulated conditions are greater than those that would be encountered during the hypothetical launch and orbital mission. The dynamic tests used followed the test specifications used for component qualification for the Applications Technology Satellite program, reference 4.

System Test Procedures were used to formalize the characteristic system operation in the atmosphere and in vacuum. These test procedures, STP's, identify the success/failure criteria of the system during and following the dynamic environmental tests, the test sequence and procedure.

The system's sensors, thrustors, valves, power and signal conditioning, and logic are characterized by the system's telemetry outputs and by total system response and operation when mounted on the single-axis test platform. Telemetry data recorded and monitored following command inputs received by the system during a test sequence are to measure a successful system operation. The completed STP's used during system qualification are included in the Data Log, reference 3.

The Qualification Test included four environmental tests: temperature storage, launch acceleration, vibration, and thermal vacuum. Photographic and recorded data of the environmental conditions associated with the tests appear in Appendix G.

A description of test specifications and test sequence used is given in the following paragraphs:

a. System Performance Test

This test is performed on the single-axis wire table facility in a vacuum of 10^{-3} torr or better. The objective of this test was to characterize the thrust and system performance of the two attitude control thrustors and associated control logic, and to operate (no thrust measurement) two station-keeping thrustors with the associated command system. All telemetry was monitored during this test.

The plenum pressure signal established the thrust variation with time parameter. The system thrust measurement is specified in STP SSD-1014.

b. Vacuum Long Form Test

This test, used only in a vacuum, was an evaluation of the system's integrity and general characterization performance. This Systems Test Procedure is specified in STP SSD-1013, Vacuum Long Form Test.

This test was part of the initial and final Systems Performance Test and is used during the Thermal Vacuum Test.

c. Atmosphere Long Form Test

This is the most extensive characterizing test that could be used with the system in air. Heater Power ON should not be commanded when the system is not in a vacuum. The thrustors will be damaged if operated hot, in air. This System Test Procedure is specified in STP SSD-1012, Atmosphere Long Form Test.

During the Qualification Test, it was used as part of the initial and final Systems Performance Tests and between the major environment tests.

d. Vibration Test (Non-Operating)

This test simulated greater than the "expected" launch vibration. The supply tank of the thrustor system was pressurized to ammonia vapor pressure with a small amount of liquid ammonia prior to the performance of these tests. The system was not operating during this environment; the electronics were attached to the dummy junction box. A single thrustor assembly was subjected to this environment. The effects of this test were checked by running an Atmosphere Long Form Test, STP SSD-1012, following the last axis vibration. To accomplish this test the dummy junction box was replaced with an adjustment box and three additional thrustor assemblies were connected into the test system.

During the vibration tests the resistojet system was subjected to a sinusoidal excitation at a rate of two octaves per minute, as shown in Figure 19. Each axis was subjected to a random excitation for four minutes at the levels shown in Figure 19.

e. Launch Acceleration (Non-Operating)

The resistojet system was subjected to a 35g acceleration along a single axis. Following the test, the system integrity was evaluated by an Atmosphere Long Form Test, STP SSD-1012.

f. Thermal Vacuum Test (Operating)

The resistojet system was subjected to a series of operating tests of at least 10^{-5} torr for non-operating and at least 10^{-3} torr while operating, with varying temperatures in the thermal vacuum chamber as follows:

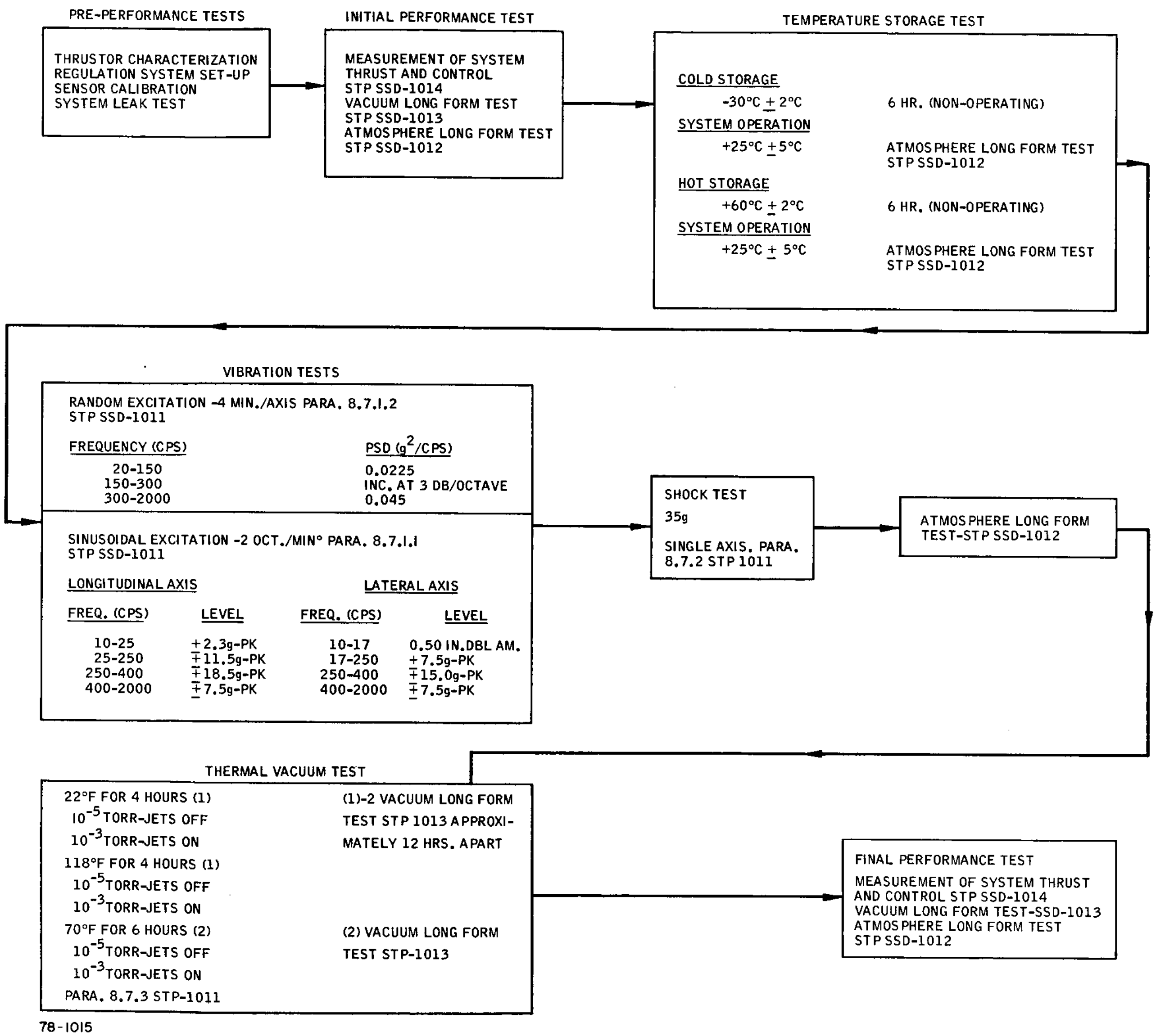

Figure 19 QUALIFICATION TESTS - RESISTOJET CONTROL SYSTEM

1) 20°F for 4 hours

2) 118°F for 4 hours

3) 70°F for 6 hours

Two Vacuum Long Form Tests, STP SSD-1013, were run at both the low and high temperature phases. During the last phase (70°F) a Vacuum Long Form Test was run during which each station-keeping thrustor was operated alternately for thirty minute cycles for a total system time (on) of six hours.

g. Temperature Storage Test

The system was subjected to a stable temperature of -30°C ±2°C for a period of six hours. Following this exposure, the temperature was increased to ±25°C, ±5°C, and an Atmosphere Long Form Test run. Stabilization was assumed when no thermocouple varied by more than 2°F.

The system was then subjected to a stable temperature of +60°C ±2°C for a period of six hours. Following this exposure the temperature was decreased to ±25°C, ±5°, and an Atmosphere Long Form Test run.

The test sequence followed for the qualification is outlined in Figure 19. The test sequence and completion approval are given in Table VIII.

2. <u>Summary of Qualification Test Results</u>

The Single-Axis Resistojet System satisfactorily passed the Qualification Test. No significant or unexplained variances were observed in the system's telemetered data during qualification. The system responded as designed to all adjustments and commands. All automatic functions performed as designed. There was never any evidence of any undesirable system interactions. Two failures were observed; both originated from the same cause, an electrical short in the coil of a solenoid valve. The valve failure was attributed to a human assembly error and not a design defect. The problems associated with the pressure transducers, previously indicated in an earlier section of this report, were present during qualification, zero shift, and high sensitivity. However, this component weakness did not result in any system failure.

One item did occur that should be considered an error of judgment rather than a system fault. The initial setting of the pressure regulation switches was not sufficiently high to accommodate the pressure drop encountered in test lines and fittings between the propellant pressure regulation and the thrustor assemblies to produce the specified thrust level. As the thrust pressure is proportional to the regulator pressure switch setting, it can be adjusted over a wide range and does not affect system qualification. Due to this adjustment error, the CW attitude control thrustor operated at 330 x 10^{-6} lb of thrust, hot during the initial system performance test. The CCW attitude control thrustor operated at 350 x 10^{-6} lb. The station-keeping thrustors were approximately at the same level. The calculation and results of the thrust performance of the attitude control thrustors are given in

Appendix H. The performance of the station-keeping thrustors is deduced from the measured nozzle box pressures and the preassembly thrustor characterization data.

One significant system adjustment was made during the test to assure that the plenum transducer power and signal conditioning were operating satisfactorily in spite of the limited range of that transducer. The pressure switches of the regulation system were reset at a lower value following the thermal vacuum test and prior to the final performance test. This caused the plenum, preplenum, and all nozzle box pressures to indicate a lower value during the final performance test. It also decreased the thrust level of the system's thrustors. The measured thrust of the CW engine was 230 x 10^{-6} lb and that of the CCW engine was 270 x 10^{-6} lb during this particular test. These thrust reductions correlate with the preassembly thrustor characterization data.

On several occasions, noise pulses transmitted to the system via the external power supply caused a resetting of the system's flip-flop controls. For example, if the CW thrustor was ON in the cold mode at the time of a high noise pulse, the CCW thrustor would come ON in the hot mode and the CW thrustor would turn OFF. If the thrustor heat enable was set at OFF and both attitude control thrustors were also OFF, and a high noise pulse occurred, both thrustors would come ON hot. As this system response is characteristic of many space electronics which require well regulated and filtered power supplies, this was not recorded as a system failure, and should not in any way be construed as one.

As an indication of system qualification, a summary of system telemetry data for two characteristic operating modes, CW thrustor ON hot and station-keeping thrustor number 1 ON hot, is presented in Table IX. This data, taken from three Vacuum Long Form Tests (the Initial Performance; the Thermal Vacuum Test, Phase III; and the Final Performance Test), shows system performance to be maintained within acceptable limits throughout the qualification.

An indication of the system's ability to respond satisfactorily to signals from a position sensor is presented in Figures 20 and 21. The figures show recorded telemetry data of position, and position plus rate, interpreted by the system's logic and processed by the system's signal conditioning. Also shown is the logic's automatic control of the attitude control thrustors, turning them ON or OFF in the hot modes, as required for light source acquisition and limit cycle position control. Note: A principal system feature is the built-in capability to adjust the control parameters and limits to accommodate different sensors, thrustors, or thrust levels.

A photograph of the installation of the complete single-axis system, including two attitude control thrustors and two station-keeping thrustors on the wire supported test platform facility, is shown in Figure 22. A close-up view of one of the mounted attitude control thrustors assemblies is shown in Figure 23.

TABLE VIII

TEST SEQUENCE AND COMPLETION APPROVALS

Task	Completion Approvals
1. Thrustor Characterization	Test Engineer:
2. Regulation System Adjustment	Test Engineer:
3. Sensor Calibration	Test Engineer:
4. System Assembly	Project Engineer:
	Test Engineer:
5. System Leak Test	Test Engineer:
6. Fuel System	Test Engineer:
7. Systems Performance Test STP SSD-1014	Test Engineer:
	Project Engineer:
8. Vacuum Long Form Test STP SSD-1013	Project or Test Engineer:
9. Atmosphere Long Form Test STP SSD-1012	Project or Test Engineer:
10a. Temperature Storage Test-Cold STP SSD-1011	Engironment Test Engineer:
10b. Atmosphere Long Form Test STP SSD-1012	Project or Test Engineer;
10c. Temperature Storage Test-Hot STP SSD-1011	Environment Test Engineer:
10d. Atmosphere Long Form Test STP SSD-1012	Project or Test Engineer:
11. Vibration Test STP SSD-1010	Environment Test Engineer:
12. Launch Acceleration Test STP SSD-1012	Environment Test Engineer:
13. Atmosphere Long Form Test STP SSD-1012	Project or Test Engineer:
14. Thermal-Vacuum Test STP SSD-1011	Environment Test Engineer:

TABLE VIII (Concl'd)

Task	Completion Approvals
14a. 22°F Vacuum Long Form Test STP SSD-1013	Project or Test Engineer: R. Angemi
14b. 22°F Vacuum Long Form Test STP SSD-1013	Project or Test Engineer: R. Angemi
14c. 118°F Vacuum Long Form Test STP SSD-1013	Project or Test Engineer: R. Angemi
14d. 118°F Vacuum Long Form Test STP SSD-1013	Project or Test Engineer: R. Angemi
14e. 70°F Vacuum Long Form Test STP SSD-1013 (see para. 8.7.3)	Project or Test Engineer: R. Angemi
15. Systems Performance Test STP SSD-1014	Test Engineer: Walter S. Davis Project Engineer: R. Angemi
16. Vacuum Long Form Test STP SSD-1013	Project or Test Engineer: R. Angemi
17. Atmosphere Long Form Test STP SSD-1012	Project or Test Engineer: R. Angemi
18. Visual Inspection	Test Engineer: Walter S. Davis Project Engineer: R. Angemi
19. Approval of Qualified Test	Program Manager: R. Pagani

TABLE IX

SUMMARY OF VACUUM LONG FORM DATA AT AMBIENT TEMPERATURE

Telemetered Data	CW Thrustor ON-HOT			Station-Keeping No. 1 Thrustor ON-HOT		
	Initial Performance Test	Ther. Vac. Phase III	Final Performance Test	Initial Performance Test	Ther. Vac. Phase III	Final Performance Test
Plenum Temperature	$81^{o}F$	$59^{o}F$	$82^{o}F$	$78^{o}F$	$58^{o}F$	$80^{o}F$
Supply Pressure	106 psia	132 psia	123 psia	103 psia	130 psia	121 psia
Plenum Pressure	6.0 psia	Saturated	4.1 psia	5.7 psia	Saturated	3.9 psia
Preplenum Pressure	6.1 psia	8.6 psia	3.6 psia	6.1 psia	8.7 psia	3.6 psia
CW Nozzle Pressure	5.6 psia	5.1 psia	3.5 psia	0	0	0
CCW Nozzle Pressure	0	0	0	0	0	0
CW Heater Current	2.0	2.3	2.9	0	0	0
CCW Heater Current	0	0	0	0	0	0
CW Heater Voltage	2.6	3.0	3.0	0	0	0
CCW Heater Voltage	0	0	0	0	0	0
SK #1 Nozzle Pressure	0	0	0	5.6 psia	5.6 psia	3.3 psia
SK #2 Nozzle Pressure	0	0	0	0	0	0
SK #1 Heater Current	0	0	0	2.7	2.9	3.1
SK #2 Heater Current	0	0	0	0	0	0
SK #1 Heater Voltage	0	0	0	2.9	2.9	2.8
SK #2 Heater Voltage	0	0	0	0	0	0
Primary Regulation Valve	Pulsing	Pulsing	Pulsing	Pulsing	Pulsing	Pulsing
System Current, Input	0.9 amp	1.0 amp	1.0 amp	0.9 amp	1.1 amps	1.1 amps

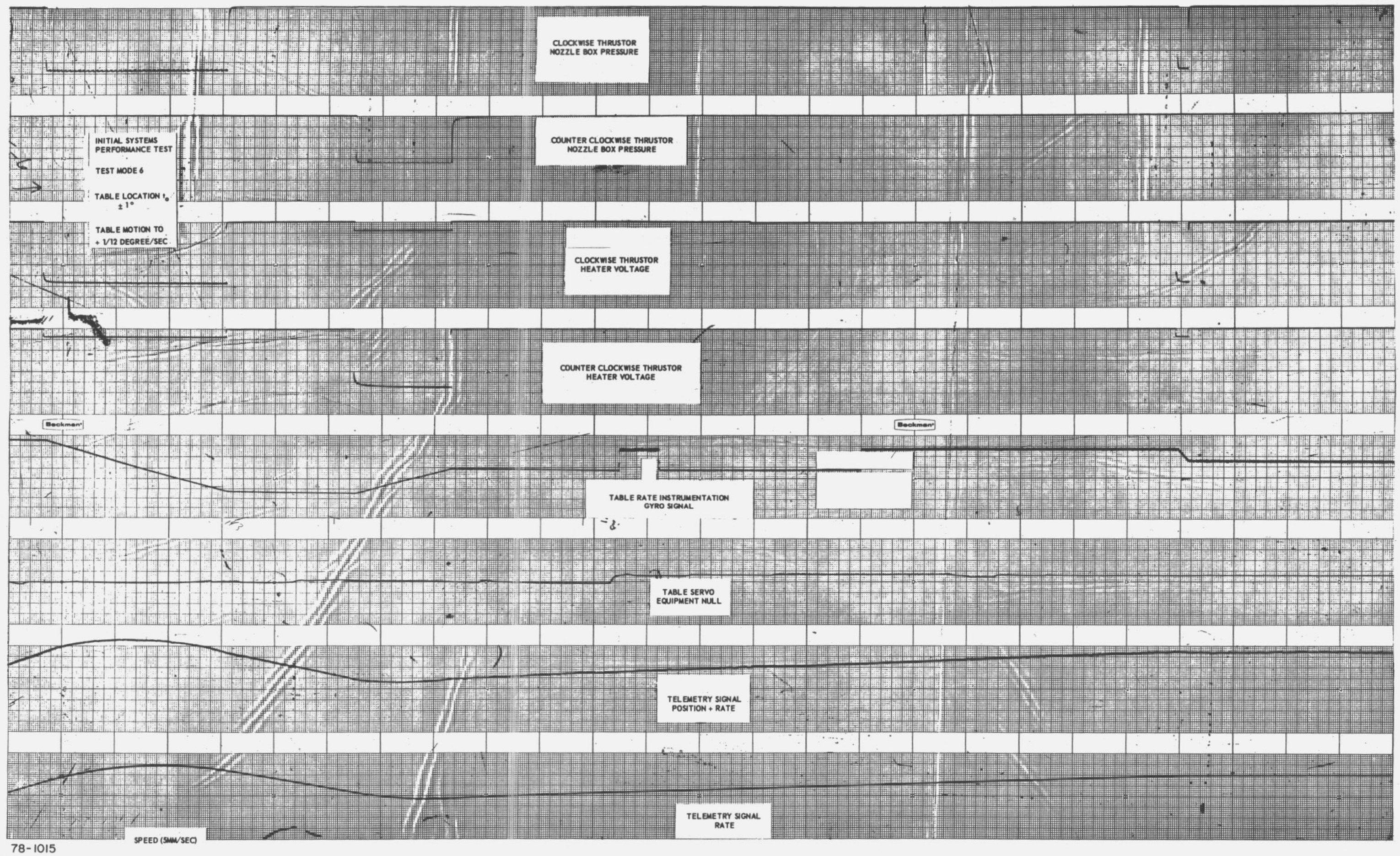

Figure 20 SYSTEM AUTOMATIC CONTROL AND PERFORMANCE-SOURCE ACQUISITION

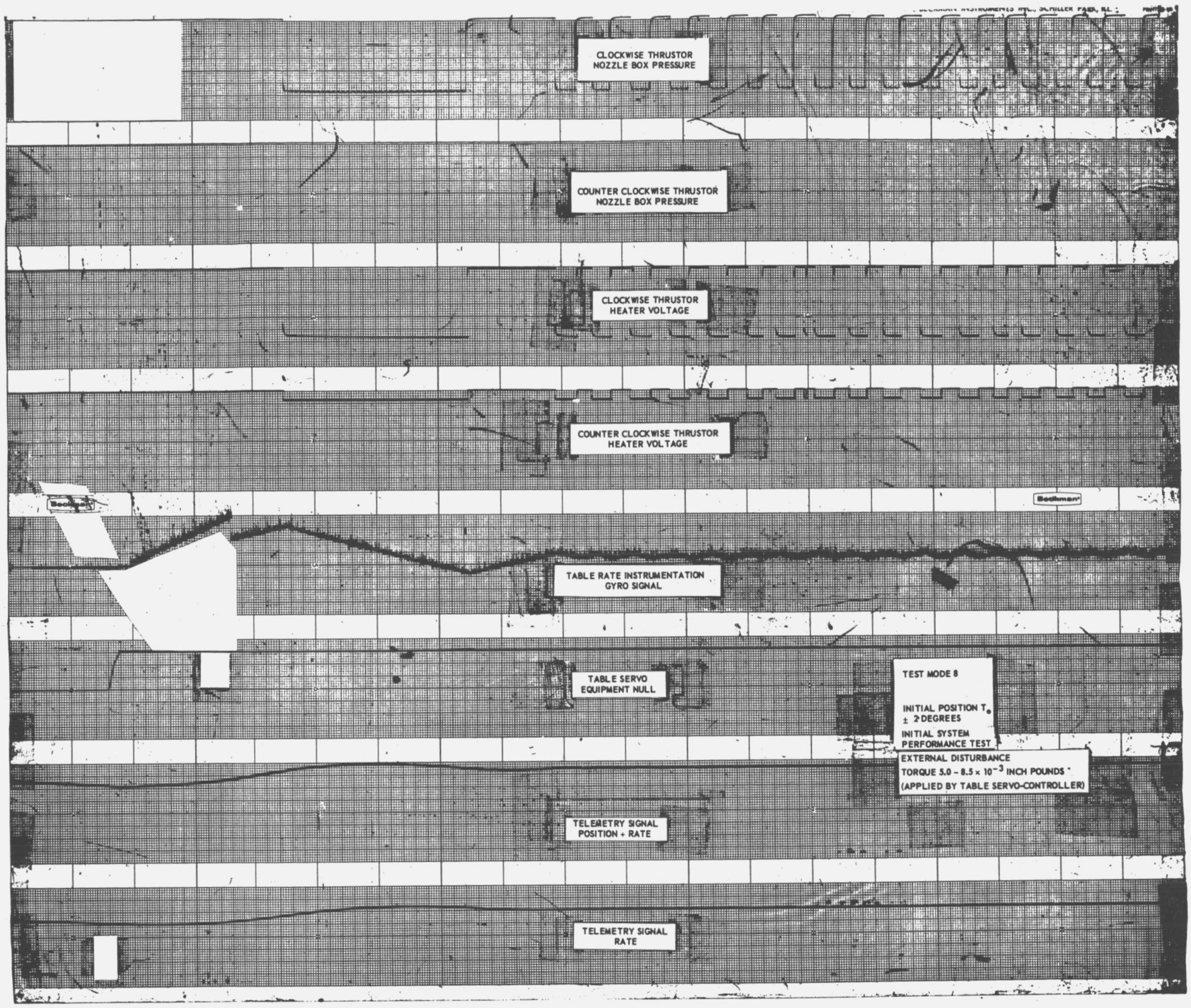

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Figure 21 SYSTEM AUTOMATIC CONTROL AND PERFORMANCE - LIMIT CYCLE OPERATION

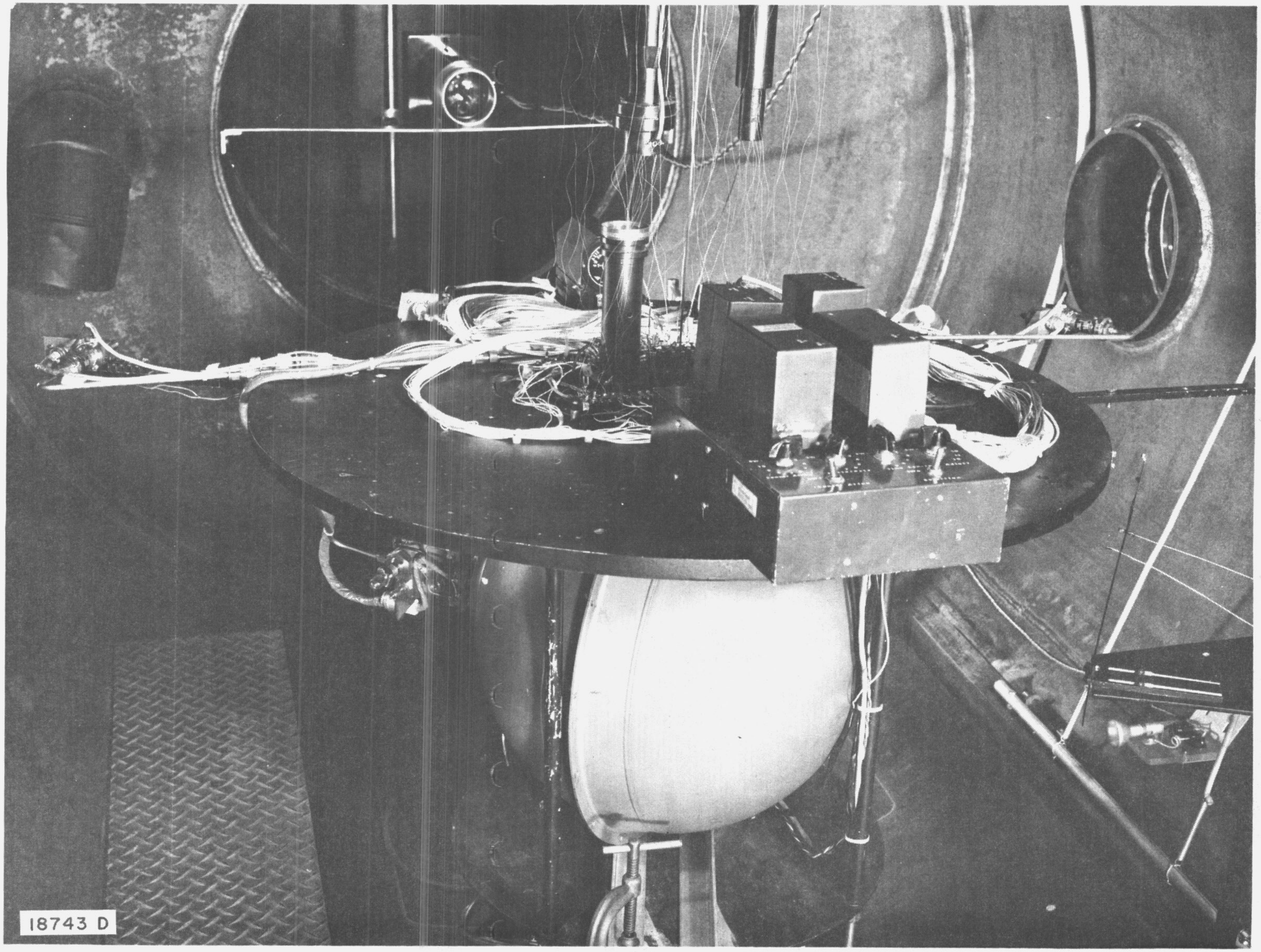

Figure 22 SYSTEM PERFORMANCE TEST OF COMPLETE SINGLE - AXIS RESISTOJET CONTROL SYSTEM

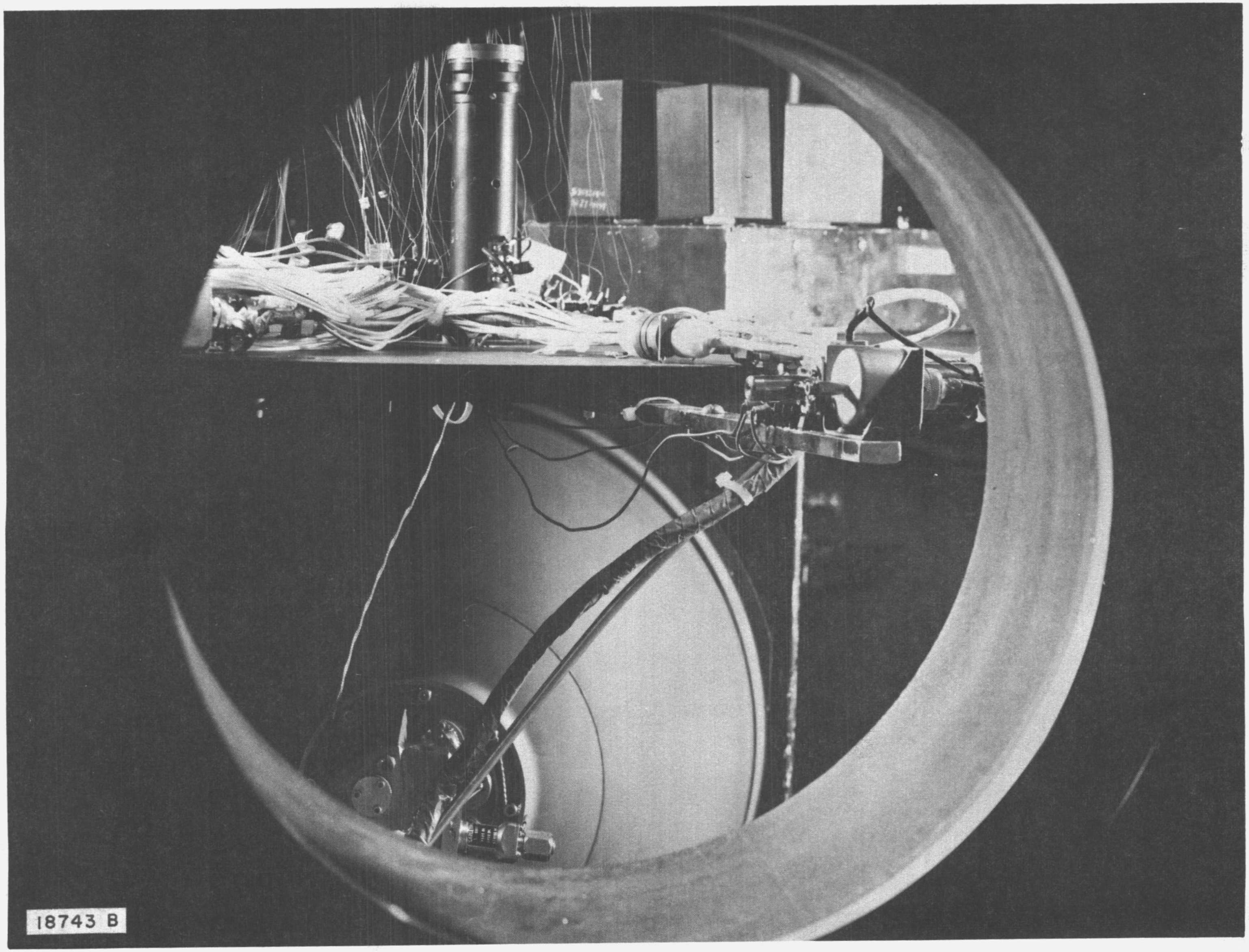

Figure 23 MOUNTED ATTITUDE CONTROL THRUSTOR ASSEMBLY, SYSTEM PERFORMANCE TEST

REFERENCES

1. Avco/SSD, Final Report on Contract NAS3-5908, entitled: "Resistojet Research and Development, Phase II," NASA CR-54688 (December 1966).

2. Avco/SSD, Semiannual Report on Contract NAS3-7934, entitled: "Design, Development, Fabrication, Test, and Delivery of Electrothermal Engine Systems," NASA CR-72104 (August 1966).

3. Avco/SSD, Data Log on Contract NAS3-7934, entitled: "Design, Development, Fabrication, Test, and Delivery of Electrothermal Engine Systems" (November 1967).

4. ATS Environmental, Qualification, and Acceptance Test Specification for Component Test, No. S2-0102, Rev. C, NASA/GSFC (1967).

5. Avco/SSD, Final Report on Contract NAS3-5908, entitled: "Resistojet Research and Development, Phase II," Supplement No. 1, NASA CR-72123 (December 1966).

APPENDIX A

PROPELLANT PRESSURE REGULATION AND FEED SYSTEM PERFORMANCE AND CHARACTERIZATION TESTS

1. Performance Tests

The effect of the dual chamber (preplenum and plenum) and the connecting orifice is shown by the plenum pressure fluctuation data in Figure A-1. These data were taken at supply pressures of 115, 135, 155, and 230 psia, over a range of flow conditions. The worst case pressure regulation conditions are a regulated pressure of 15 psia, liquid flow from the storage tank at 155 psia, and a propellant use rate of 20 x 10^{-6} lb/sec. Under these conditions, the system controlled pressure to ± 1.01 percent. For all other flow or pressure conditions specified in the contract, it was possible to control regulated pressure to better than ± 1.0 percent.

The data of Figure A-2 also demonstrate the effect on regulated pressure variation caused by the deadband of the pressure switch. The C2069 switch has a normal dead band of 4.5 psia. The C2069-1 switch has a dead band of 1.5 psia. To obtain ± 1.0 percent regulated pressure control, the pressure switch should be selected for its appropriate range of operation. This is indicated in Table A-I. (Note: There is in the system a basic tradeoff between valve cycling rate and pressure regulation variation--the better the control, the higher the valve cycling rate.)

TABLE A-I

PRESSURE SWITCH EFFECTS

Pressure Switch Mod. No.	Normal Operating Range (psid)	Normal Dead Band ($lb/in.^2$)	Setting (psia)	Maximum Preplenum Pressure Variation (percent)	Maximum Regulated Plenum Pressure Variation (percent)
C2069-1	1-15	1.5	15	53	1.01
C2069-3	5-50	4.5	15	80	4.86
C2069-3	5-50	4.5	50	22	0.95

Sections of recorded system performance data are shown in Figures A-3, A-4, and A-5.

As indicated previously, the regulation system has been designed with a parallel redundancy of two regulating valves and two pressure switches. In this system, one switch is set at a pressure slightly below (0.5 $lb/in.^2$) the other and would commence controlling the pressure when the plenum-preplenum pressure dropped the additional 0.5 $lb/in.^2$ due to flow usage.

Early analytical predictions were nearly correct concerning the adequacy of the thermal capability of the system to provide the energy for ammonia vaporization. For the worst condition (i.e., a maximum flow rate, 248×10^{-6} lb/sec at 20^oF for 208 seconds, with 3.30 pounds of propellant remaining in the storage tank), the system was able to maintain the specified control. During this test, the pre-plenum flange temperature was monitored. The data shown in Figure A-6 were taken during two tests at station-keeping flow conditions with liquid ammonia entering the regulation system. The temperature of the propellant storage tank remained nearly constant for these runs. A third test was made withdrawing gaseous ammonia for 660 seconds. The total system temperature change was less than 1^oF. This is also shown in Figure A-6. Recorded data from these tests are shown in Figure A-7.

2. Pre-Performance Regulation System Characterization

The system plenum was set up with a C2069-2 switch as the primary switch and a C2069-3 switch as the secondary. The regulator valves were Carleton Model 1809-001-41. The system was the same as the delivered system except no diodes were across the pressure switches and a lab transducer was used in the plenum instead of the delivered transducer.

The regulation system was operated with the switches referenced to atmosphere (14.65 psia). The primary valve was set to open at 19.05 psia ($\Delta P = 4.4$ psia) and the secondary valve was set at 18.70 psig ($\Delta P = 4.05$ psi). The flow was withdrawn from the system approximately at the actual flow conditions, about 3×10^{-6} lb/sec.

The system was operated on the primary and secondary system with both ammonia liquid and gas flow through the valve. A summary of the regulation data is given in Table A-II and shown graphically in Figure A-8.

TABLE A-II

SUMMARY OF THE REGULATION DATA

Valve	Media	P Supply (psig)	P (psia)	Period (sec)
1	gas	80	.15	3.8
2	gas	80	.15	3.8
1	liquid	140	.25	7.2
2	liquid	140	.30	8.4

In addition to the steady-state operation, several "starts" of the system were simulated. In this instance, the plenum was evacuated and a regulator value turned on. A sample of a leak check and a simulated start is shown in Figure A-8. It can be seen there is very little overshoot in plenum pressure, and thus no change or switch damage due to overpressure.

The transient situations of gas to liquid operation, and liquid to gas operation were simulated. In all cases, the regulation was good, and no discrepancies in system performance were noted.

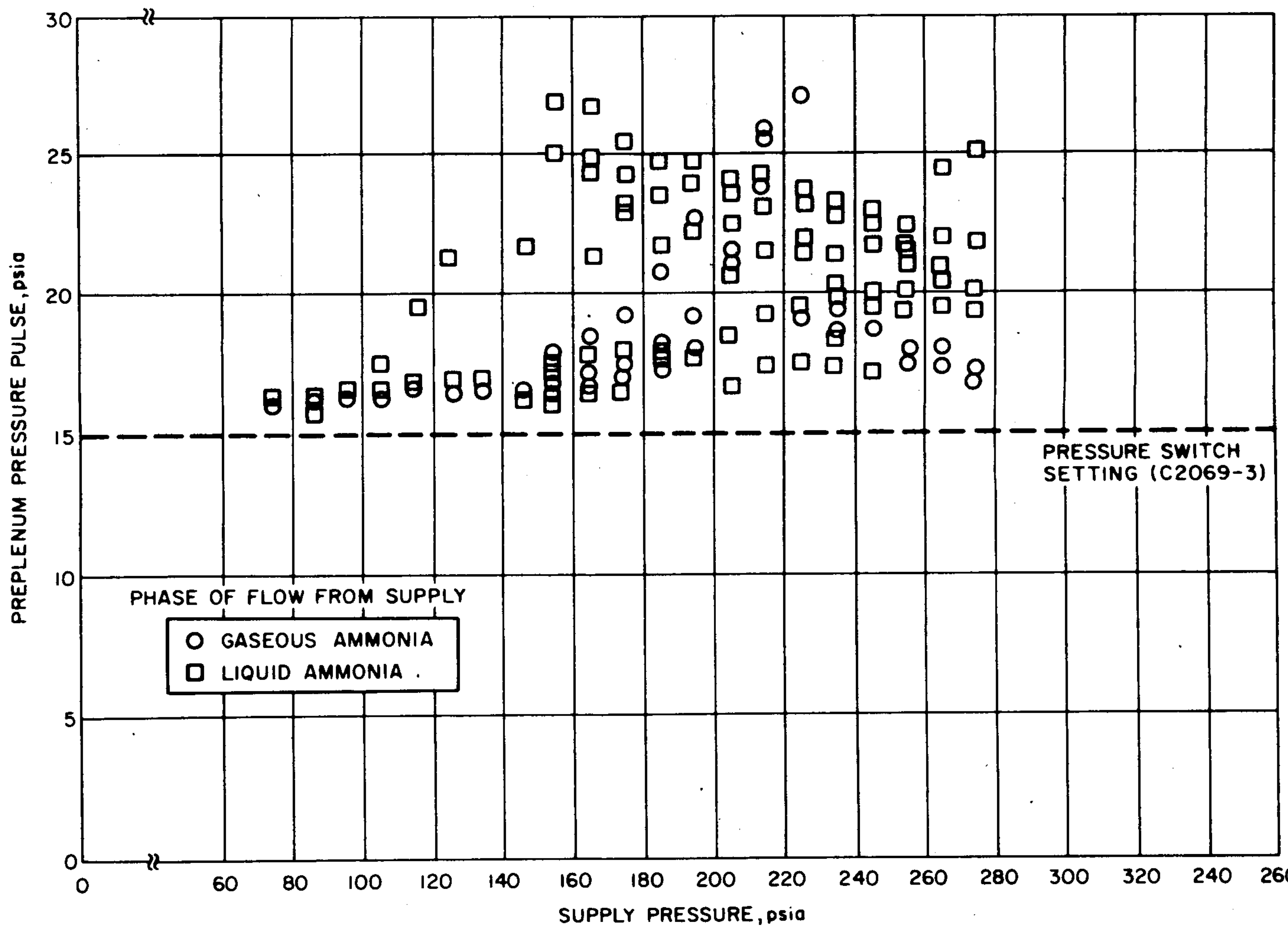

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Figure A-1 PREPLENUM PRESSURE PULSE VERSUS PROPELLANT SUPPLY PRESSURE

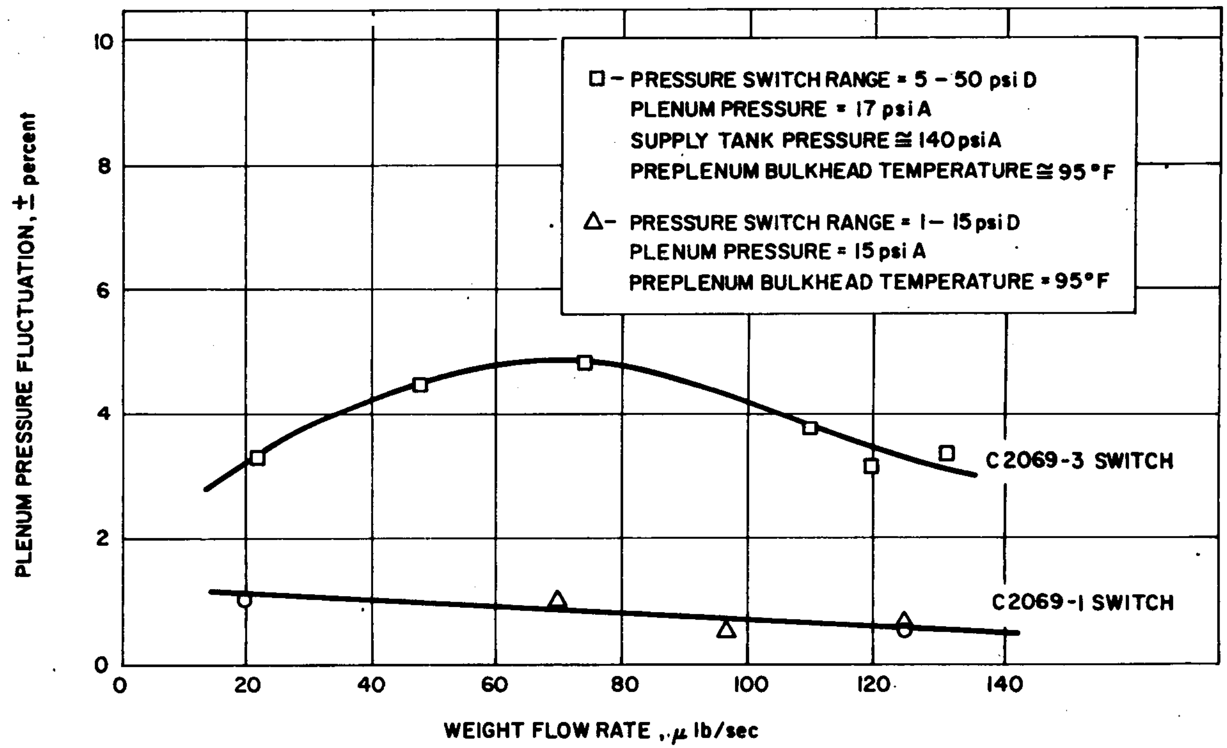

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Figure A-2 REGULATED PLENUM PRESSURE VERSUS PROPELLANT USE RATE

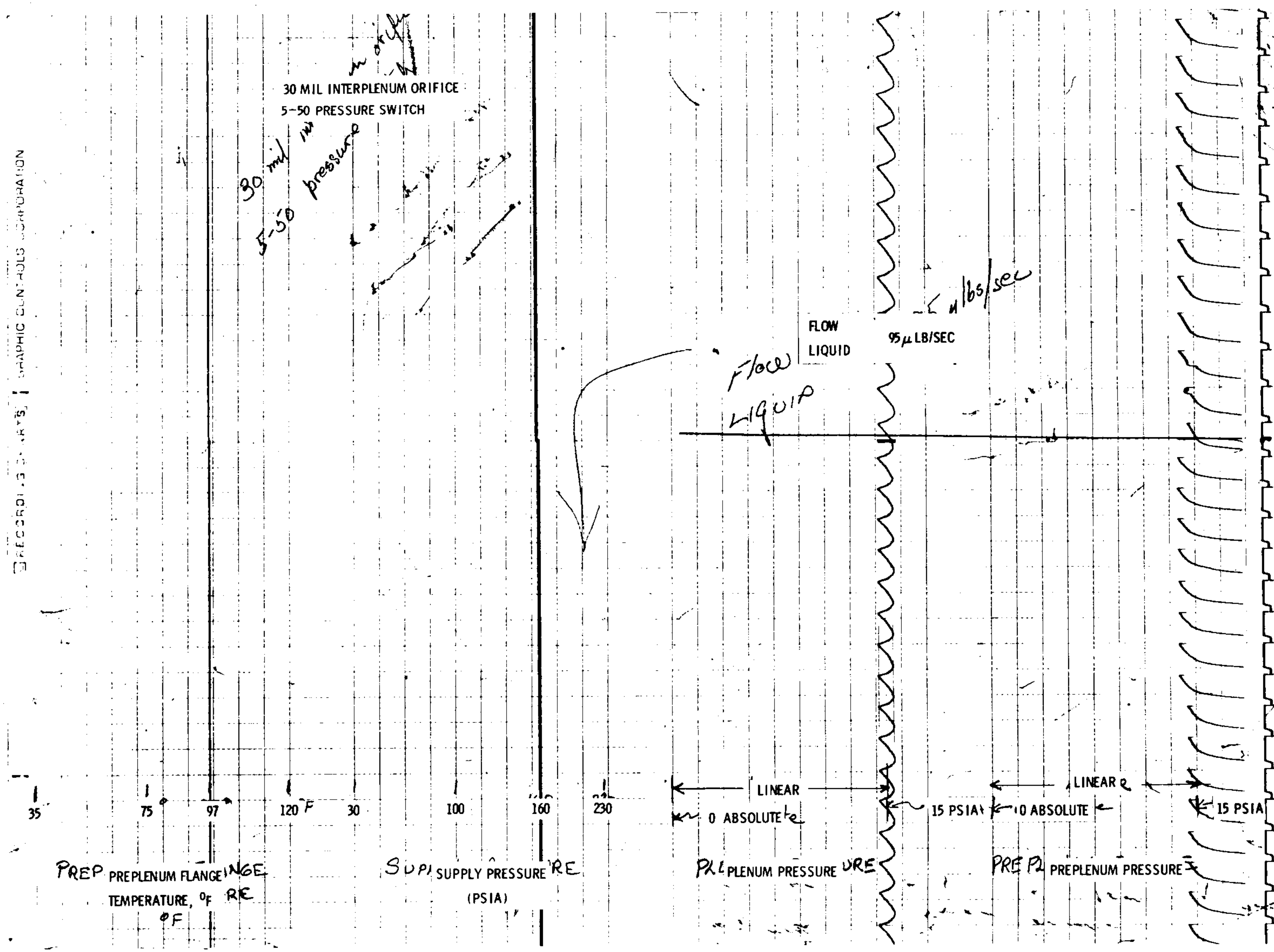

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Figure A-3 SYSTEM PERFORMANCE DATA: LIQUID FLOW, 30-MIL ORIFICE
5-50 PRESSURE SWITCH

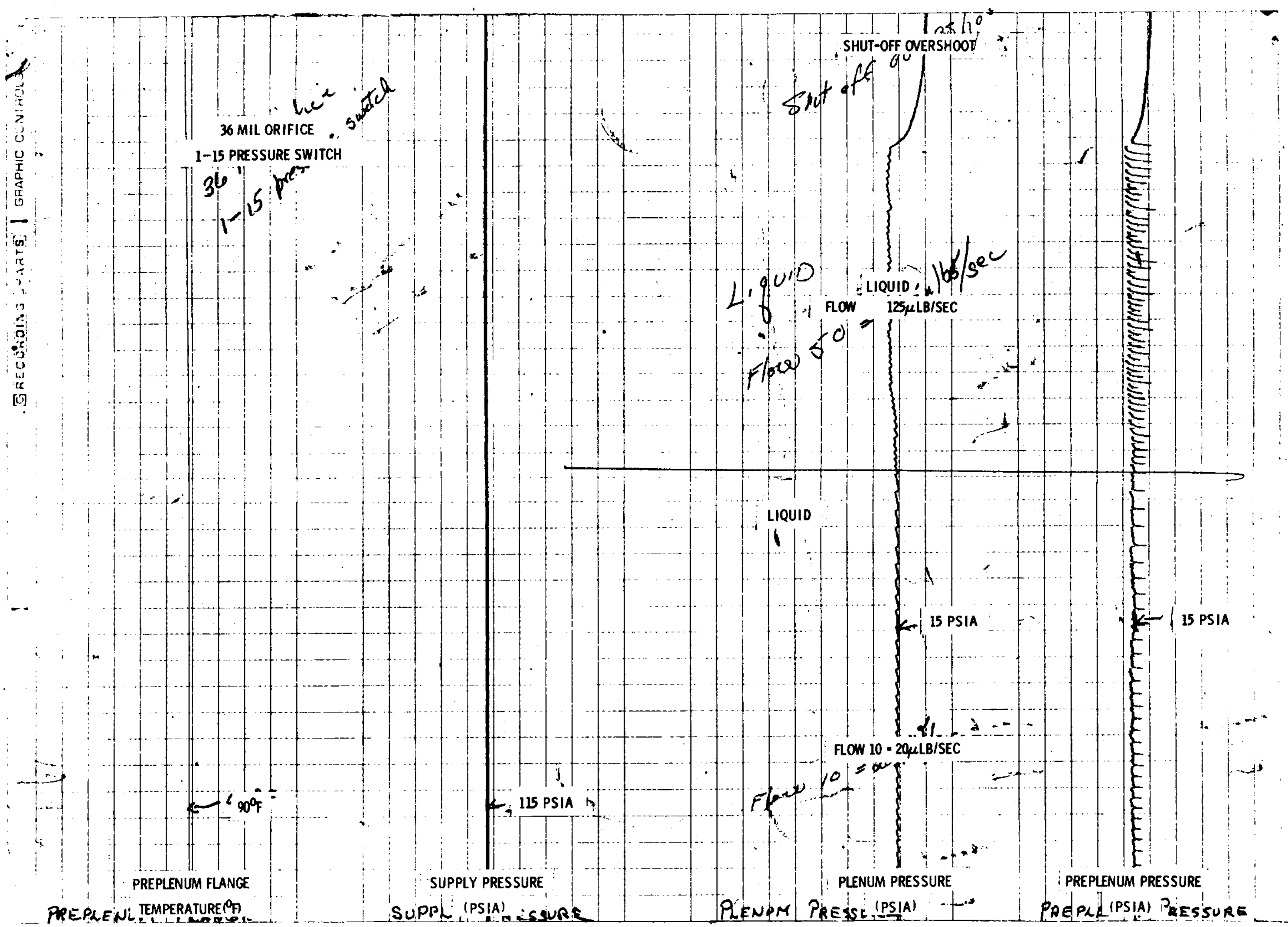

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Figure A-4 SYSTEM PERFORMANCE DATA: LIQUID FLOW, 36-MIL ORIFICE, 1-15 PRESSURE SWITCH

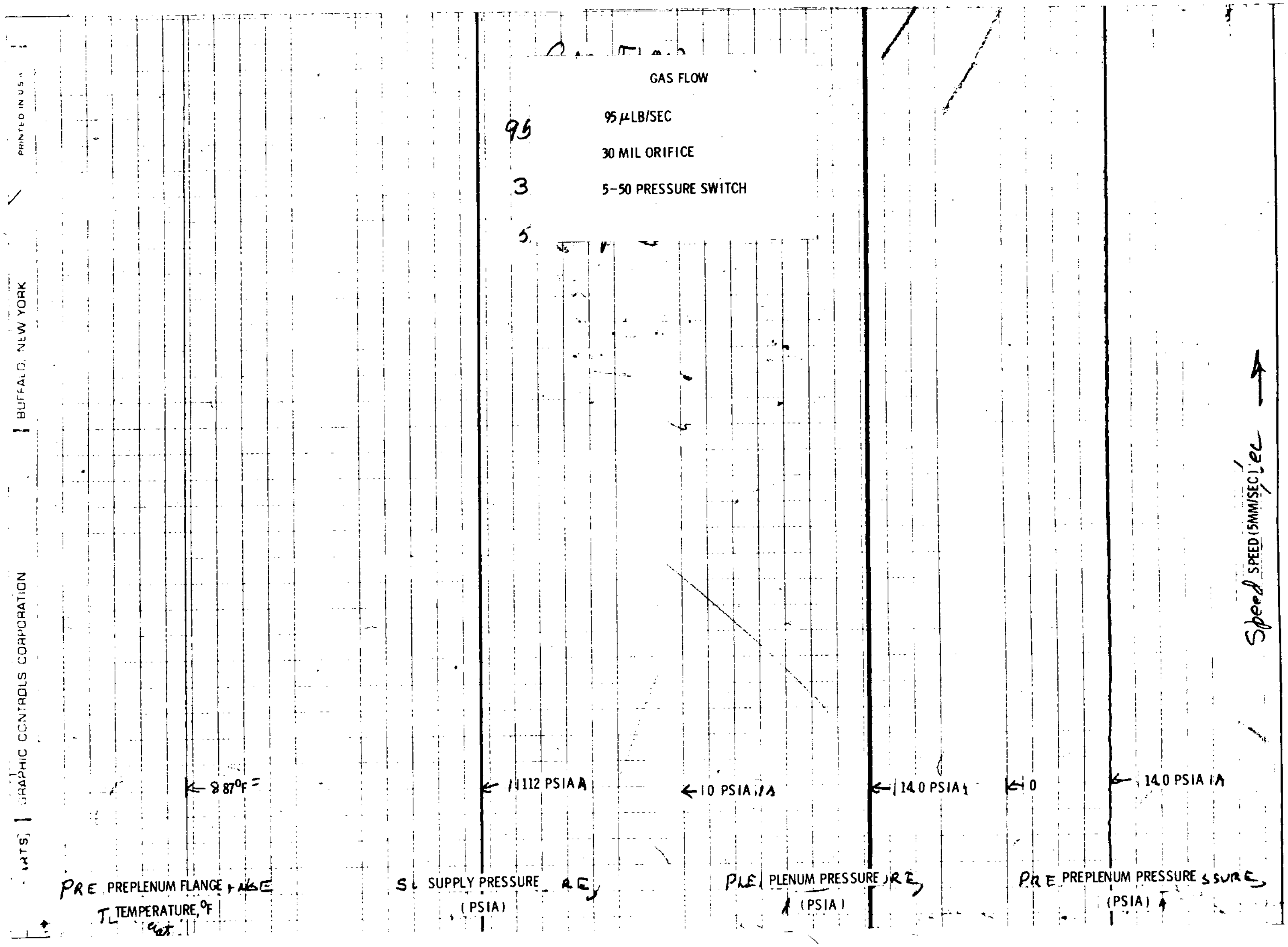

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Figure A-5 SYSTEM PERFORMANCE DATA: GAS FLOW, 30-MIL ORIFICE, 5-50 PRESSURE SWITCH

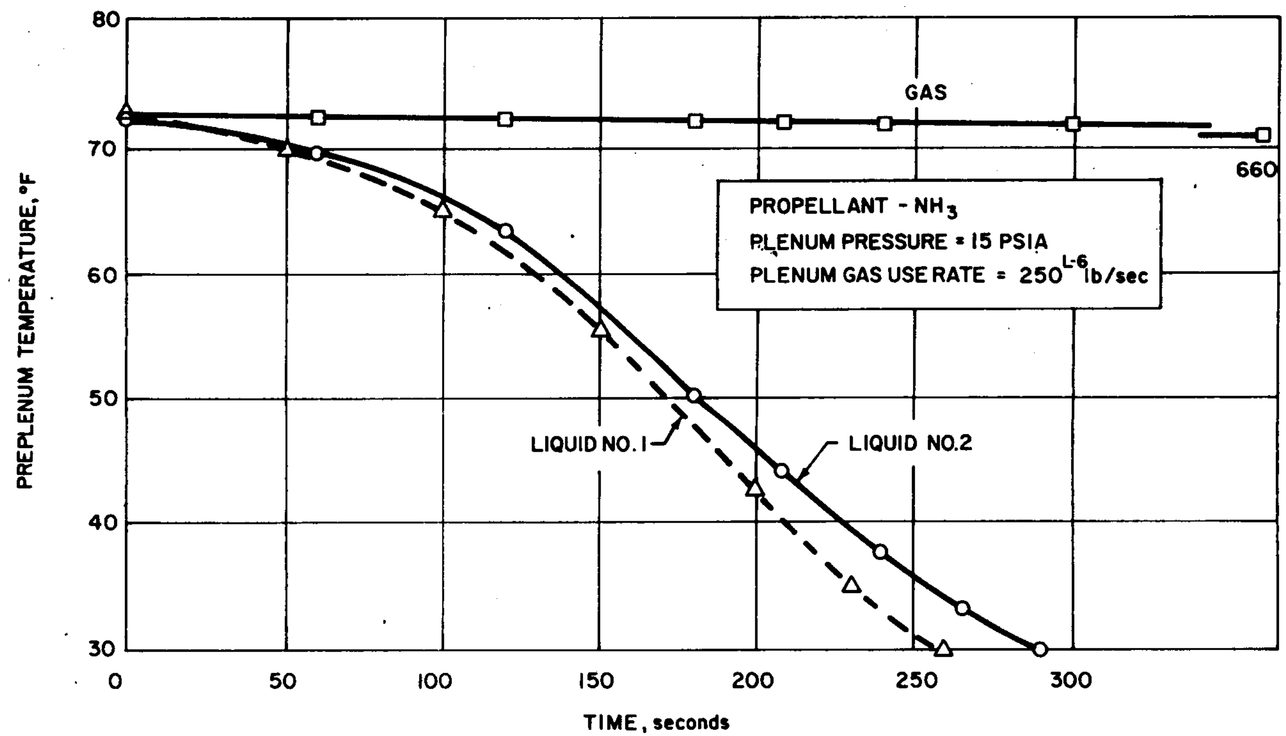

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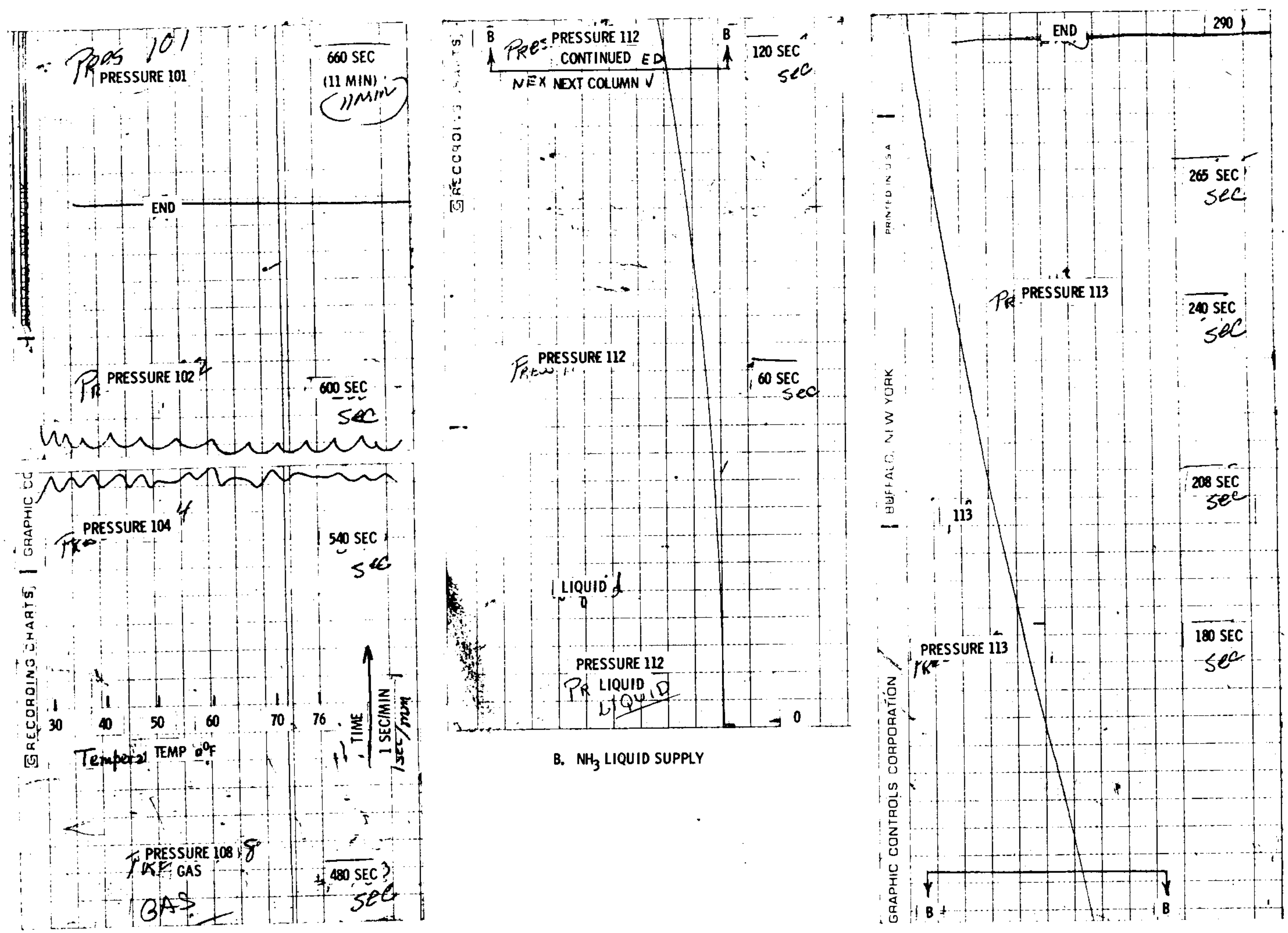
Figure A-6 PREPLENUM FLANGE THERMAL HISTORY FOR LIQUID AND GAS OPERATION



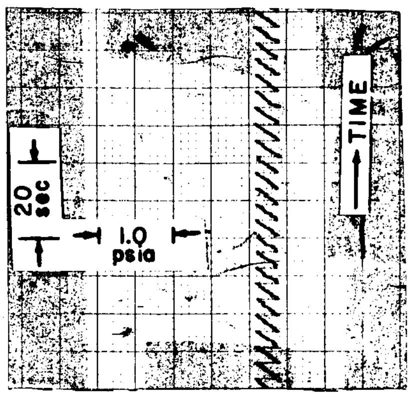
A. NH_3 GAS SUPPLY

B. NH_3 LIQUID SUPPLY

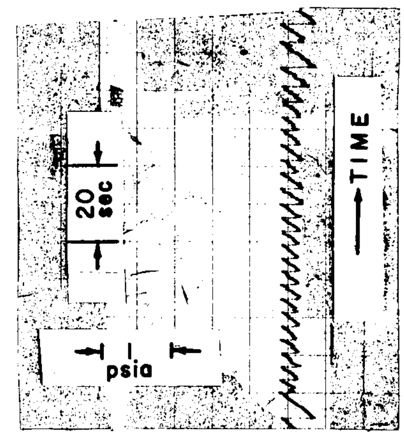
B. LIQUID TEST (CONTINUED)

770810 D

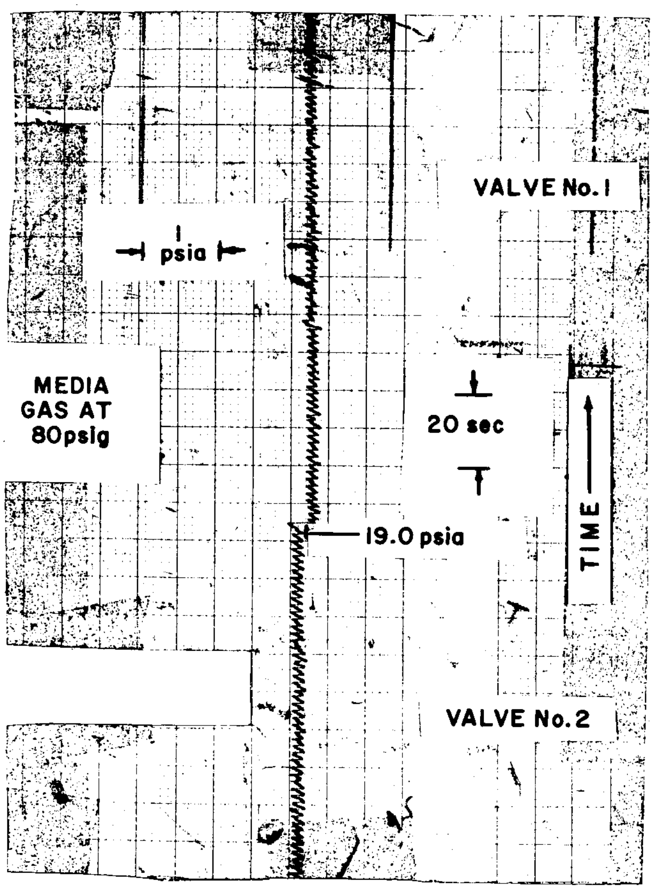
Figure A-7 REPRESENTATIVE PREPLENUM THERMAL DATA



VALVE 2 LIQUID 140psig



VALVE I LIQUID 140psig



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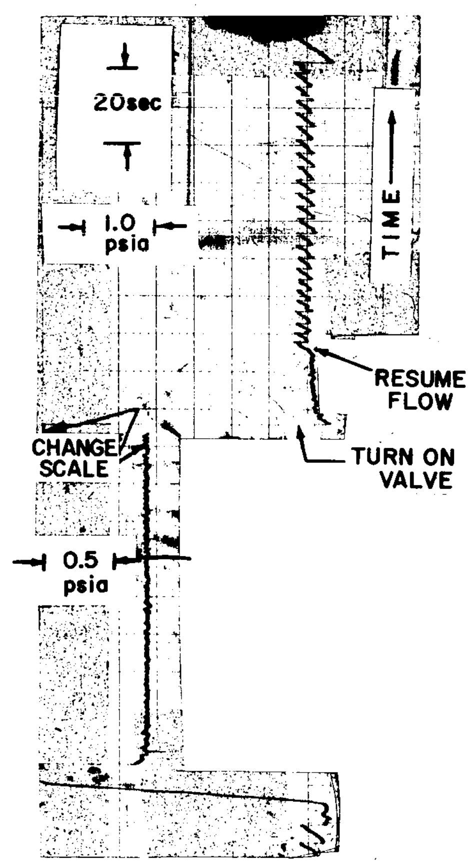
REGULATION OPERATION WITH GAS



LEAK TEST WITH SYSTEM ACTIVATION WITH VALVE I

Figure A-8 REGULATION CHARACTERIZATION

APPENDIX B

AMMONIA PROPELLANT FUELING PROCEDURE, EQUIPMENT, AND SYSTEMS

Three factors are considered here for the fueling operation: (1) the purity of the propellant, (2) the cleanness of the fueling equipment (particularly the connecting points), and (3) the amount of propellant transferred. The actual fueling procedure is outlined below, together with several general comments about the operation.

1) Evacuate storage tank to at least 1 torr, and maintain vacuum pumping for 1 hour. Then, close fill valve and turn off and disconnect pump. This allows sufficient and accurate fill of ammonia and reduces contamination of the tankage system.

2) Use a stainless steel pressure container for portage of the ammonia to the storage tank. This container should be equipped with a 1/4-inch Kel-F seat manual valve (Whitey Type) and a very short length of 1/8-inch stainless steel tubing, having an AN-type fitting for attachment to the fill valve. The container should be ultrasonically cleaned (no chlorine), evacuated, weighed, and then filled with high-purity ammonia (careful not to overfill). The container is then reweighed and connected, and the ammonia transferred to the tank. The container is again weighed to determine the amount transferred. (Over-filling can occur should the density of the liquid ammonia increase during the transfer process, and should the container be nearly filled with higher density ammonia: when the ammonia is warmed, the density decreases and extreme pressures can be obtained.)

3) After connecting to the fill valve, the fill valve is opened with a 9/16-inch wrench by turning the thin concentric nut counter-clockwise until it again begins to indicate resistance to turning. (Before operating system, operator should be familiar with the valve.) Allow a small amount of ammonia to be transferred into the storage tank. Close the manual transfer line valve and then the storage tank fill valve. Allow tank to arrive at ambient conditions. This will accomplish the following:

a) Control the rate of pressure rise in the storage tank.

b) Allow for leak checking in system.

c) Allow subsequent liquid transfer with a minimum of local temperature drop. (When liquid flashes into the evacuated tank and impinges on the wall opposite the fill tube, a large local temperature drop will occur.)

4) Re-open storage tank fill valve, and then open manual transfer line valve to continue fuel transfer process. Fueling now should be accomplished as quickly as possible in order to keep the time available for liquid expansion short.

The filling procedure is accelerated if the fill container is higher than the exit tube. To further accelerate the transfer, a heat gun may be directed over the fill container; be certain, however, that both the fill valve and hand valve are open before applying heat. Another technique is to chill the propellant storage tank. This may be done with ice packs, ice bath, or cooling coils.

Usually, the completion of the transfer can be determined by the end of the sound of running liquid. The fill valve is then closed with 5 inch-pounds of torque, the hand valve shut off, and the pressure in the transfer line released slowly as the connecting fittings are loosened. (This transfer line should be kept extremely short downstream of the hand valve.) This procedure is repeated until sufficient porpellant has been transferred.

The total tank volume has been measured at 2796 cubic inches. Therefore, the maximum amount of NH_3 that should ever be loaded is 56.0 pounds. It is advised that for laboratory usage, the tank should not be loaded with more than 50 pounds.

APPENDIX C

THRUSTOR RESEARCH

1. Nozzle Divergence Angle

A series of five expansion nozzles were made, having included angles of 30, 45, 60, 75, and 90 degrees. Each nozzle had a reamed 13-mil diameter throat with no inlet champer. Each had an expansion ratio ϵ of about 25. No heater tube was used in conjunction with the nozzle, so only cold data at about 80°F was taken.

A metering orifice, 26 mils in diameter, was located upstream of the nozzle box. This orifice was calibrated by two techniques: for high flow conditions, calibration was by a weight change rate of the propellant supply container; and for low flow conditions, by the rate of pressure change in the vacuum chamber in which the nozzle was operated. This calibration data is given in Figure C-1. For the range of interest, the curve is nearly linear. Tests were made with each of the nozzles at several nozzle pressures with gaseous ammonia propellant. The data obtained is presented in tabular form in Table C-I. Thrust measurements were made on the Avco wire table facility.

The performance in terms of thrust is shown in Figure C-2. No correlation is evident on the basis of divergent angle. The 90° points are uniformly low, the 75° and 30° points are high, and the 45° points are somewhat low. The scatter for a given set of points is not large, but the curves for the sets of points differ by as much as 10 percent. The comparison on the basis of specific impulse which should neutralize the effect of throat variations is given in Figure C-3.

As in Figure C-2, the 30° points appear high and the 90° points low. Thus, there seems to be evidence to indicate that the 30° angle is better than the 90° angle, but not enough to say that it is a monatonic relationship.

To obtain an indication of the effects caused by several of the nozzle-orifices, the data in Figure C-4 was obtained.

2. Thrustor Performance Versus Pressure

A study was made to establish what effect thrustor pressure would have on performance. A series of tests were made using a thrustor of the standard design as shown in Figure 12. Flow to the thrustor was controlled and maintained upstream of the thrustor. Thrust data was obtained with no heat to the thrustor heater and with five watts (see Figure C-5). As mass flow was measured during these tests, specific impulse versus pressure was also obtained and is given in Figure C-6. It is noted that specific impulse for unheated ammonia for thrust levels of 50 to 800 x 10^{-6} pound of thrust is a constant 90 ±5 seconds and is 70 ±7 seconds at 5 x 10^{-6} pound of thrust. Application of 5 watts to the thrustor heater increased the specific impulse by 40 to 60 seconds over this thrust range.

3. Thrustor Performance Versus Throat Diameter

To determine if thrustor throat diameter affected thrustor performance (specific impulse) two nozzles, without heater tubes, were compared. One had a 30-mil throat and the other a 10-mil throat. From the thrust and mass flow measurements obtained, the specific impulse data of Figure C-7 was calculated. Plotted on the same figure is some data from the standard thrustor. Though a difference of specific impulse is observed when the data is shown versus pressure (Figure C-7), the effect is just that of specific impulse decreases with thrust.

4. Thrust Measurement Accuracy

As indicated previously, the thrust measurements are made on Avco's wire table facility. This facility has been described previously in reference 2. As thrust measurements are a direct function of the output of the table gyro, tests were made to verify the stability of its sensitivity. These tests, each lasting 1/2 to 3/4 hour, were made with a constant table rate applied. During these tests, no variation of gyro output was observed. The gyro was optically calibrated to determine the linearity of its sensitivity curve. The resultant curve is shown in Figure C-8. Point scatter from linearity is very small.

Thrust measurement on the facility as a function of table position and velocity was also evaluated. Velocity tests with a thrustor operating at 10^{-6} lb of thrust did not indicate any problem (Figure C-9). The "best fit" curve varied from 10.8 μ lb at -4 times the earth's rotational rate, e_o, to 10.2 at + 4 e_o. The scatter limit curve varied from ± 3.5 percent at -4 e_o to ± 2 percent at 4 e_o. As these measurements were made at random table positions, it is concluded that there is no apparent effect caused by table position.

TABLE C-I

NOZZLE EXPANSION ANGLE TESTS

Nozzle	Run	P_c	I_{sp}	F	$\dot{m}$
Divergence Total Angle (°)	No.	Nozzle Box Pressure (psia)	Engine Specific Impulse (sec)	Engine Thrust (μlb)	Weight Flow Rate NH_3 (μlb/sec)
60	1	3.0	85.4	580	6.80
	2	3.03	84.4	582	6.90
	3	3.03	87.7	609	6.94
	4	1.95	95.5	396	4.15
	5	1.95	93.0	390	4.19
	6	1.19	98.8	227	2.30
	7	3.95	84.5	779	9.22
	8	5.00	86.2	1015	11.79
45	9	2.85	86.4	544	6.30
	10	1.33	94.8	232	2.45
	11	4.95	84.7	960	11.32
90	12	1.20	90.9	207	2.28
	13	2.95	81.4	526	6.47
	14	5.00	76.7	885	11.52
75	15	1.40	94.8	251	2.65
	16	3.08	87.5	610	6.98
	17	4.90	87.0	1011	11.61
30	1	5.00	89.2	1140	12.79
By CPK	2	3.00	89.5	643	7.19
	3	1.00	96.6	177	1.83

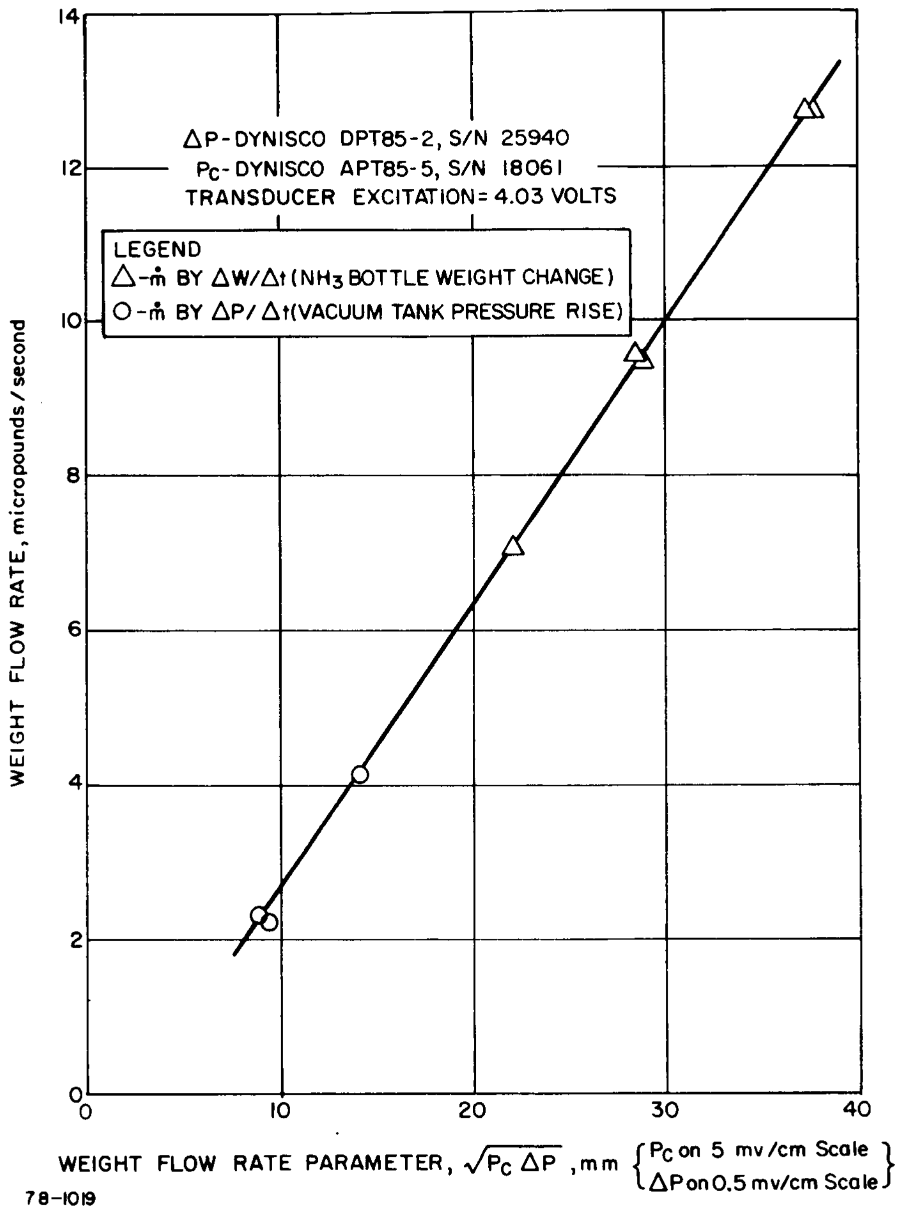


Figure C-1 26-MIL DIAMETER METERING ORIFICE CALIBRATION

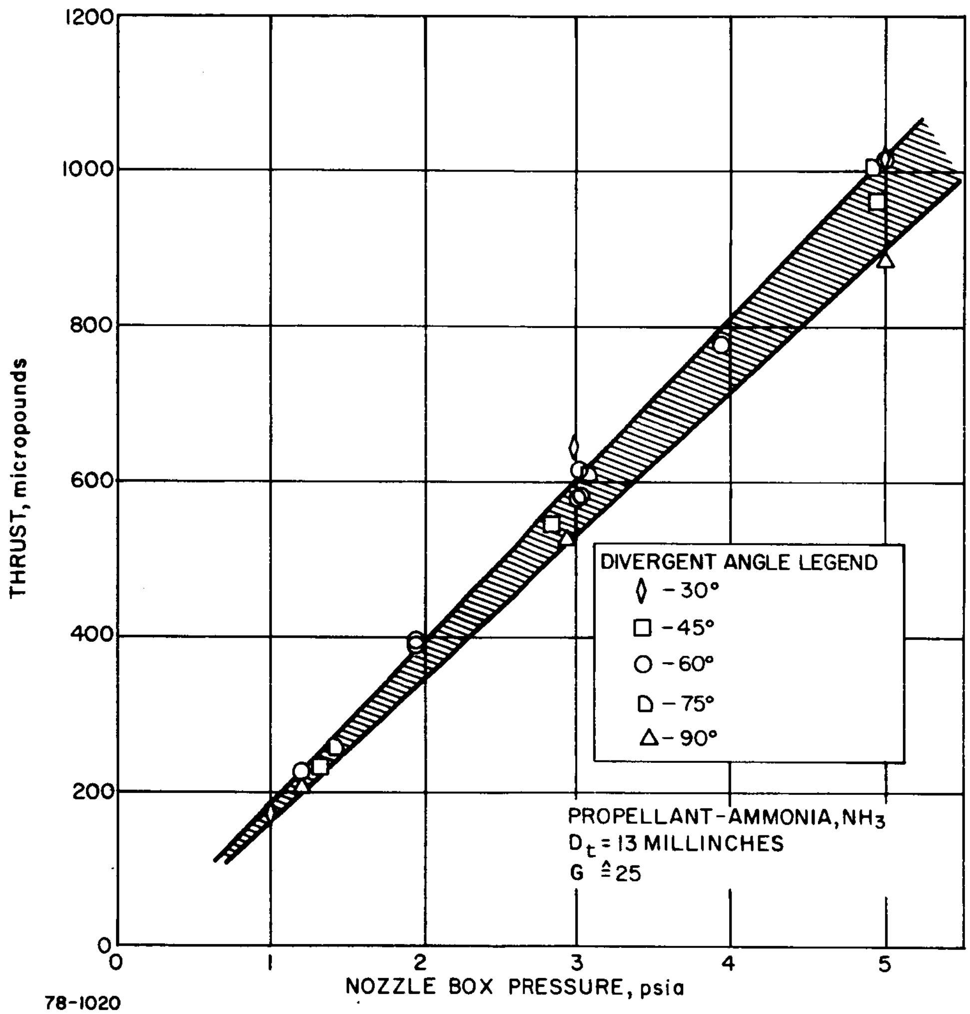


Figure C-2 THRUST PERFORMANCE OF EXPANSION NOZZLES

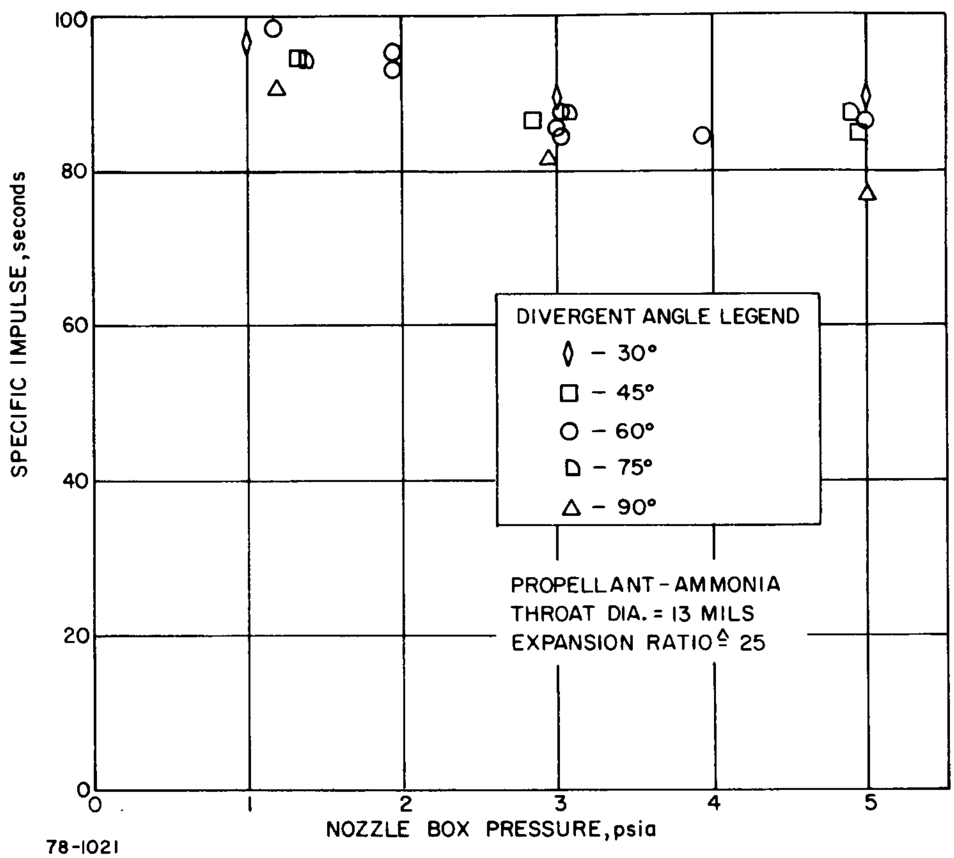


Figure C-3 SPECIFIC IMPULSE COMPARISON OF EXPANSION NOZZLES

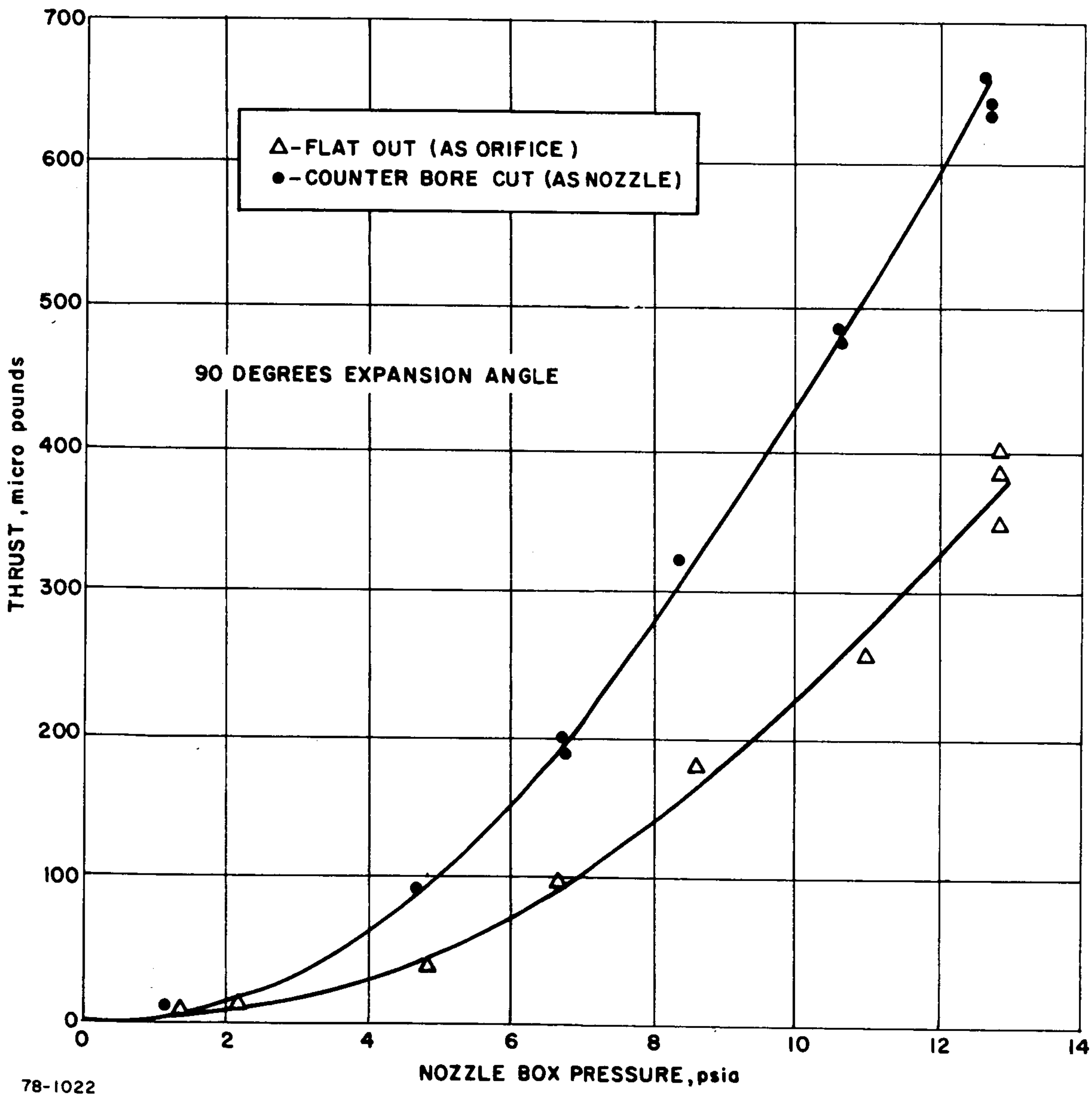


Figure C-4 THRUST PERFORMANCE COMPARISON OF NOZZLE-ORIFICE

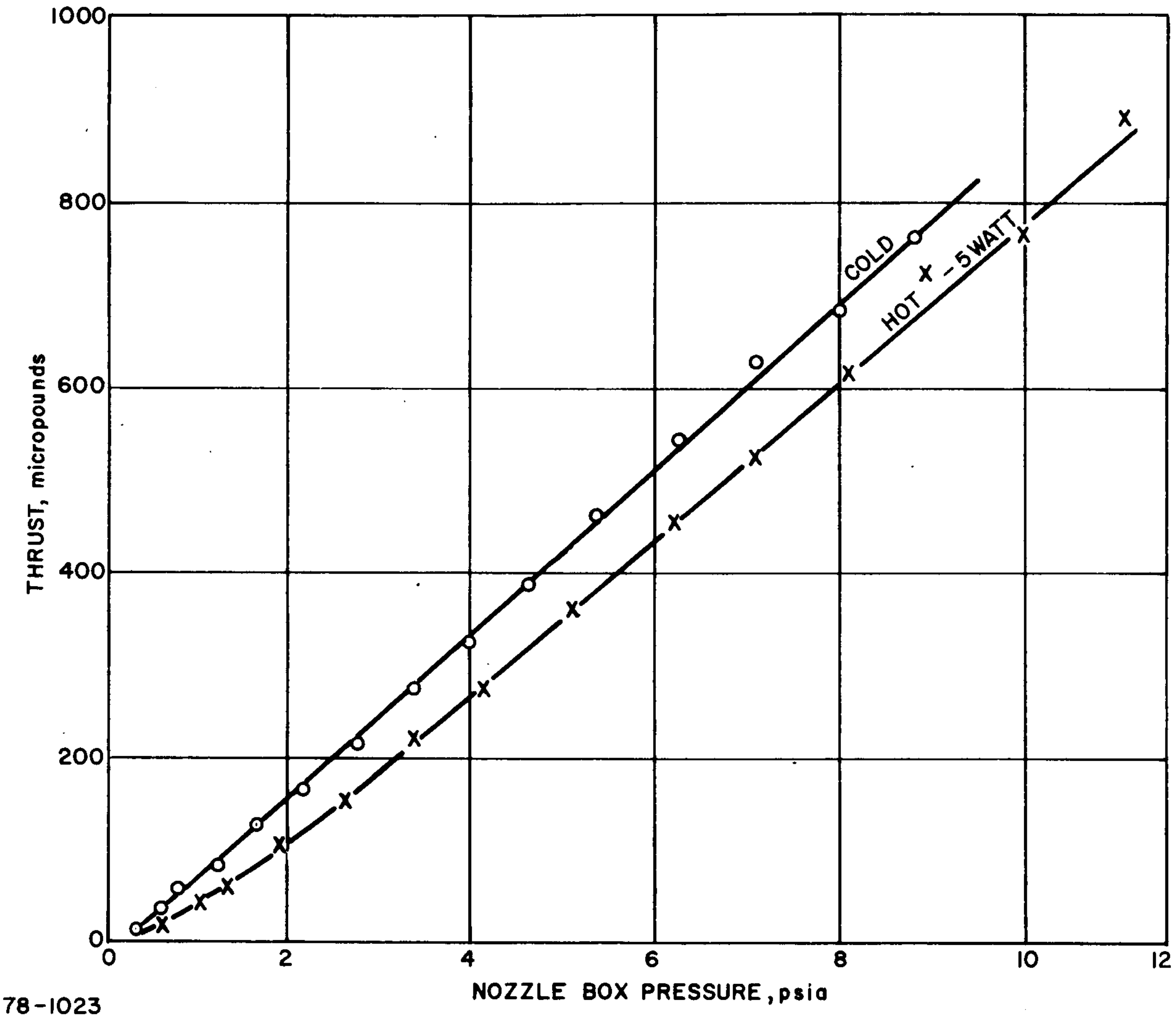


Figure C-5 THRUST PERFORMANCE VERSUS PRESSURE

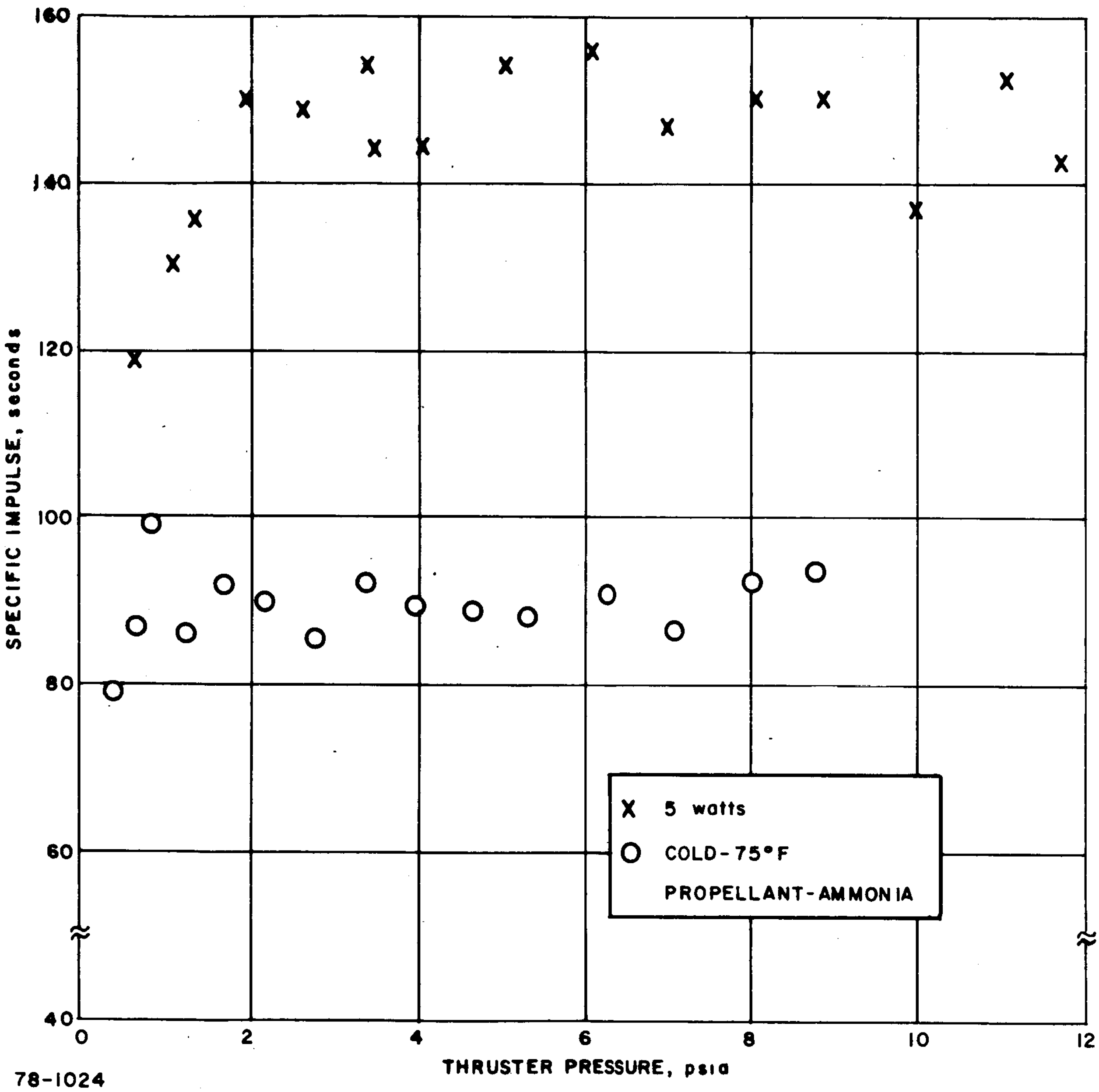


Figure C-6 SPECIFIC IMPULSE VERSUS THRUSTOR PRESSURE

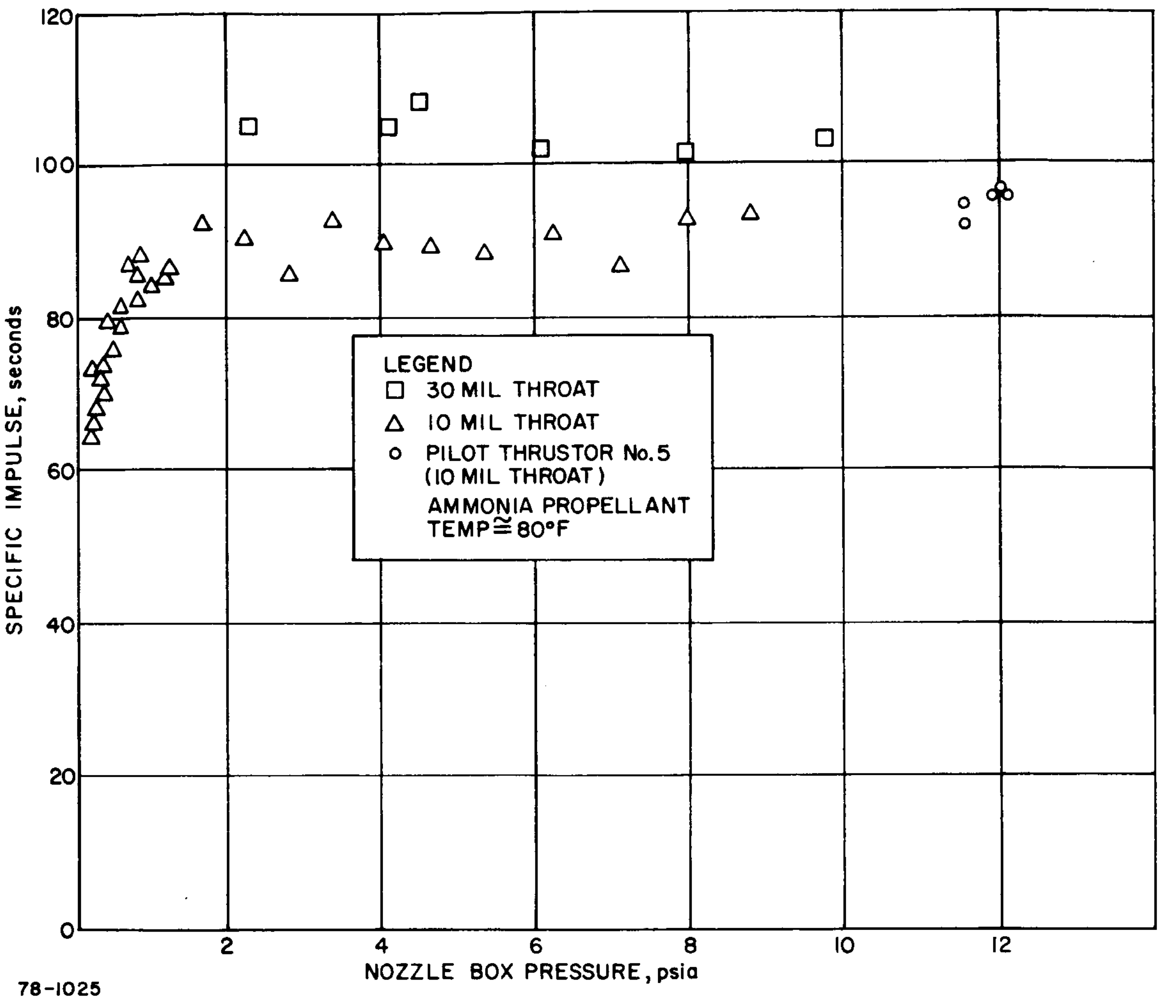


Figure C-7 NOZZLE THROAT DIAMETER TESTS

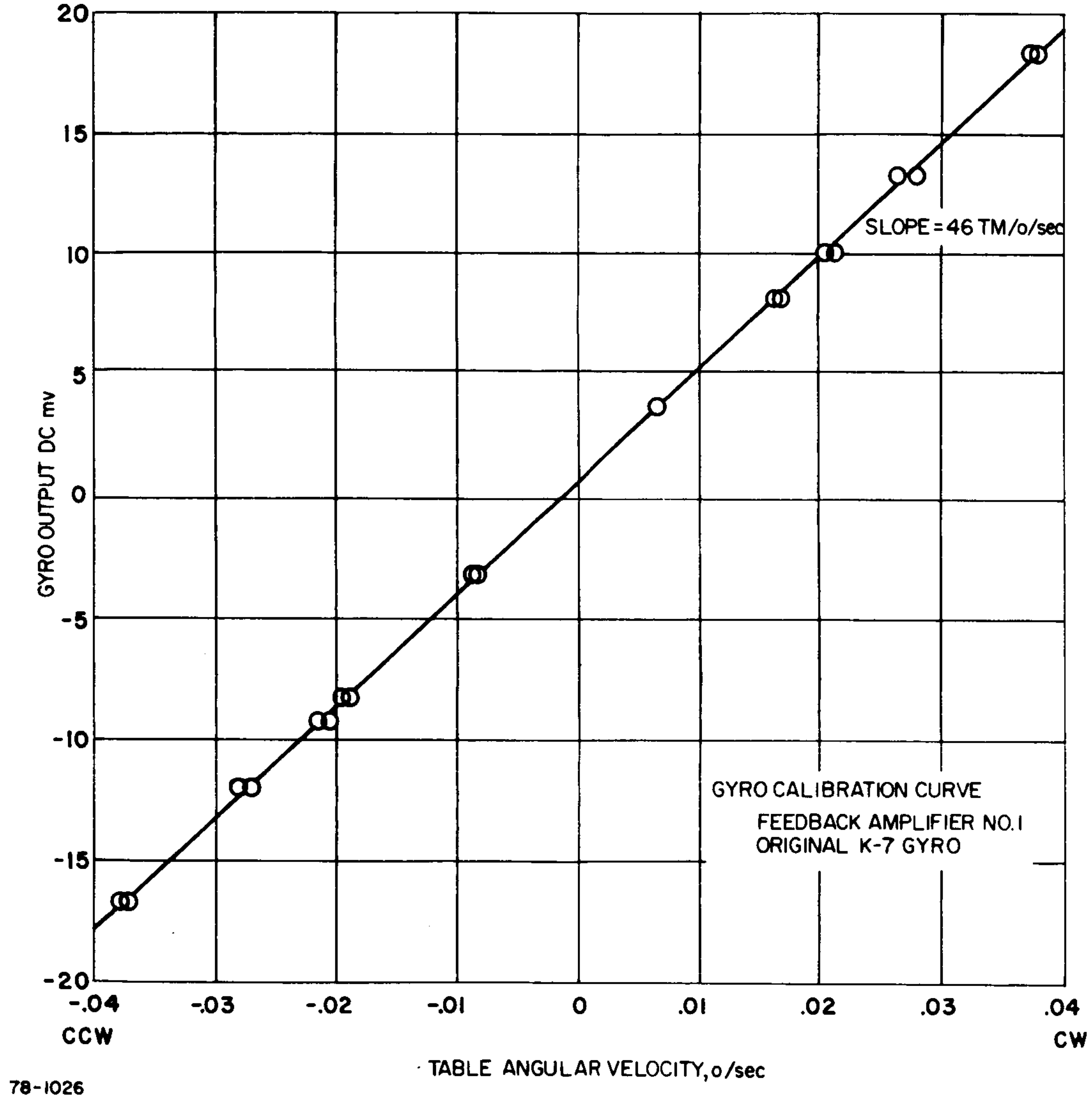


Figure C-8 GYRO SENSITIVITY CALIBRATION CURVE

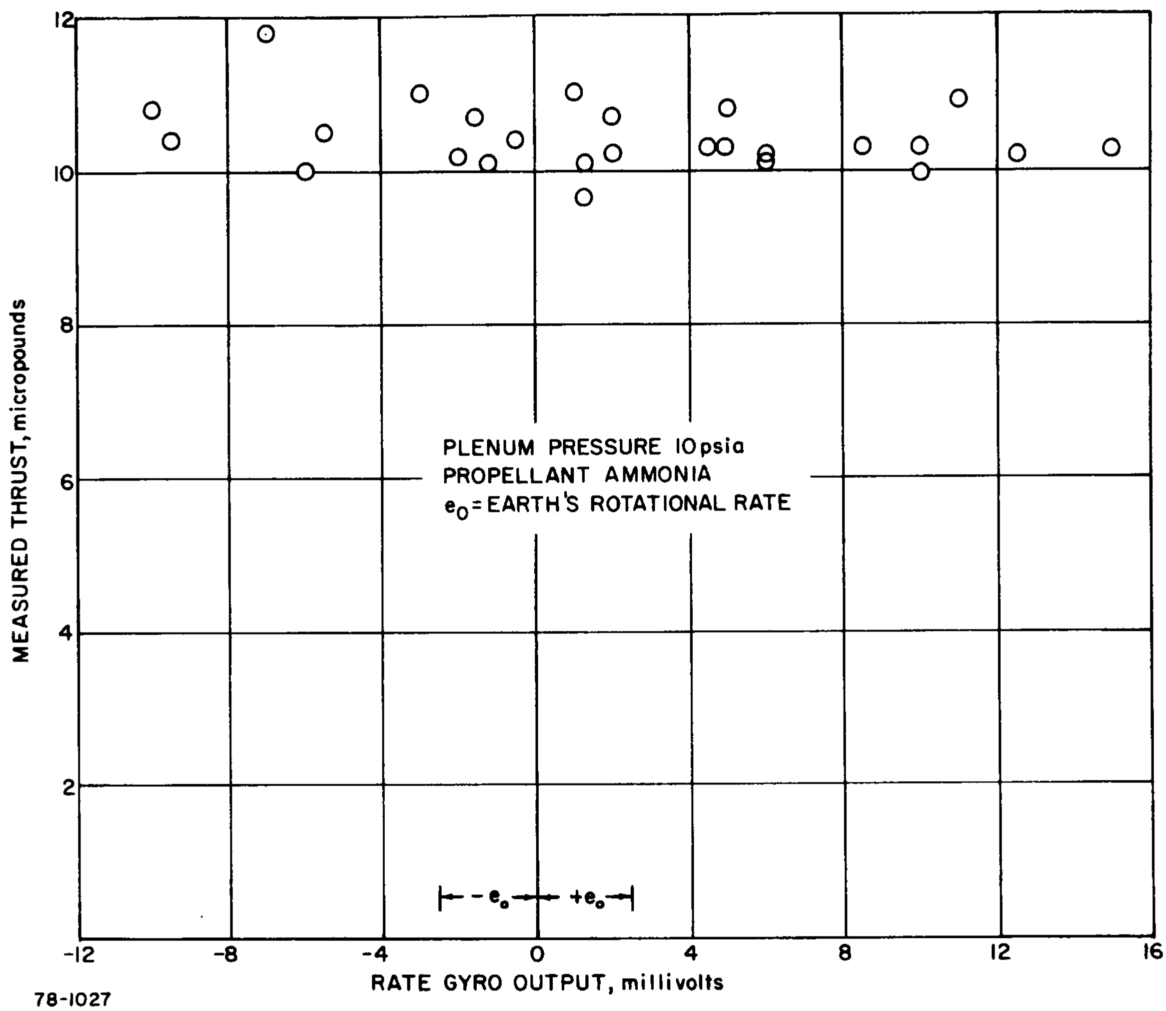


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Figure C-9 THRUST AS FUNCTION OF TABLE VELOCITY

APPENDIX D

MEASUREMENT OF THRUST VECTOR

A critical parameter in the application of a spacecraft reaction system is thrustor alignment. This alignment required determination of the relationship between thrustor geometry and actual thrust vector. A method has been developed which can establish this relationship to better than ± 1/4 of a degree. To make this measurement, each thrustor is provided with a mirror surface on its end cap (see Figure D-1). A partial cross-hair is scribed on the mirror surface so as to contain the nozzle axis at its origin and in a manner which designates a polarity on the horizontal and vertical planes (see Figure D-1). As an example, the two angles which locate the thrust vector relative to a perpendicular to the mirror passing through the nozzle throat would be $+\theta_H$ and $-\theta_V$ for the vector drawing on Figure D-1.

These horizontal and vertical angles are determined singularly--each requiring a separate thrustor setup on the measurement apparatus and a wire supported test platform, a schematic of which is shown in Figure D-2. The thrustor is mounted on the Block B such that the cross-hair lies horizontal and vertical, with the scribed portion of the horizontal hair pointing to the left (will designate positive angle direction). The nozzle Block B, which can be swiveled by remote actuation of motor drum D against the tension of spring C, provides the thrustor with propellant gas at pressure levels similar to what the unit will see in operation. When the chamber in which the wire table is mounted has been evacuated to less than 0.1 micron, the thrustor is actuated. If the thrust vector lies outside the vertical plane which contains the table support wire and the nozzle throat, a torqui will be applied to the table of mangitude

$$T = Fd \qquad \text{(D-1)}$$

where

T = torque

F = thrust

d = moment arm

By adjusting the position of the thrust vector by swiveling the nozzle B, a position can be found for which the measured torque output is zero. When this occurs, the thrust vector lies in the vertical plane containing the support wire and nozzle, and the lever arm d is zero. Because the wire table has a minimum resolution limit, the vector lies within ±0.25° of that plane. With the thrustor orientation locked relative to the table, the table is then rotated into the line of sight of an optical galvanometer which is positioned such that the line of sight contains the table support wire. When the thrustor cross-hair lines up with the galvanometer cross-hair, a reading is taken of the scale reflection from the mirror. Because

$$20 = \tan^{-1} \frac{(S)}{L} = \frac{S}{L} - 1/3 \frac{(S)^3}{L} + \cdots = \frac{S}{L}\left[1 - 1/3 \frac{(S)^2}{L} + \cdots\right] \qquad \text{(D-2)}$$

and since for $\theta_{max} = \pm\ 4°$

$$\frac{S}{L} = \tan \pm\ 4° = \pm\ 0.07$$

and

$$1/3 \left(\frac{S}{L}\right)^2 = 0.0016$$

then for less than a 0.2 percent error,

$$\frac{S}{L} = 20 \quad \text{or} \quad \theta = \frac{S}{2L} \text{ (radians)} \tag{D-3}$$

Measurements of L give its dimension as 105.5 cm, so

$$\theta = \frac{57.3\ S}{2\ (105.5)} \text{ (degrees)} = 0.272\ S \tag{D-4}$$

Using this technique, the data shown in Table D-I was taken on four thrustors.

TABLE D-I

THRUST VECTOR ORIENTATION

Thrustor	θ_H (degrees)	θ_Y (degrees)
A	+0.94	+0.67
B	+0.02	+1.36
C	-0.03	+0.16
D	-2.04	+0.49

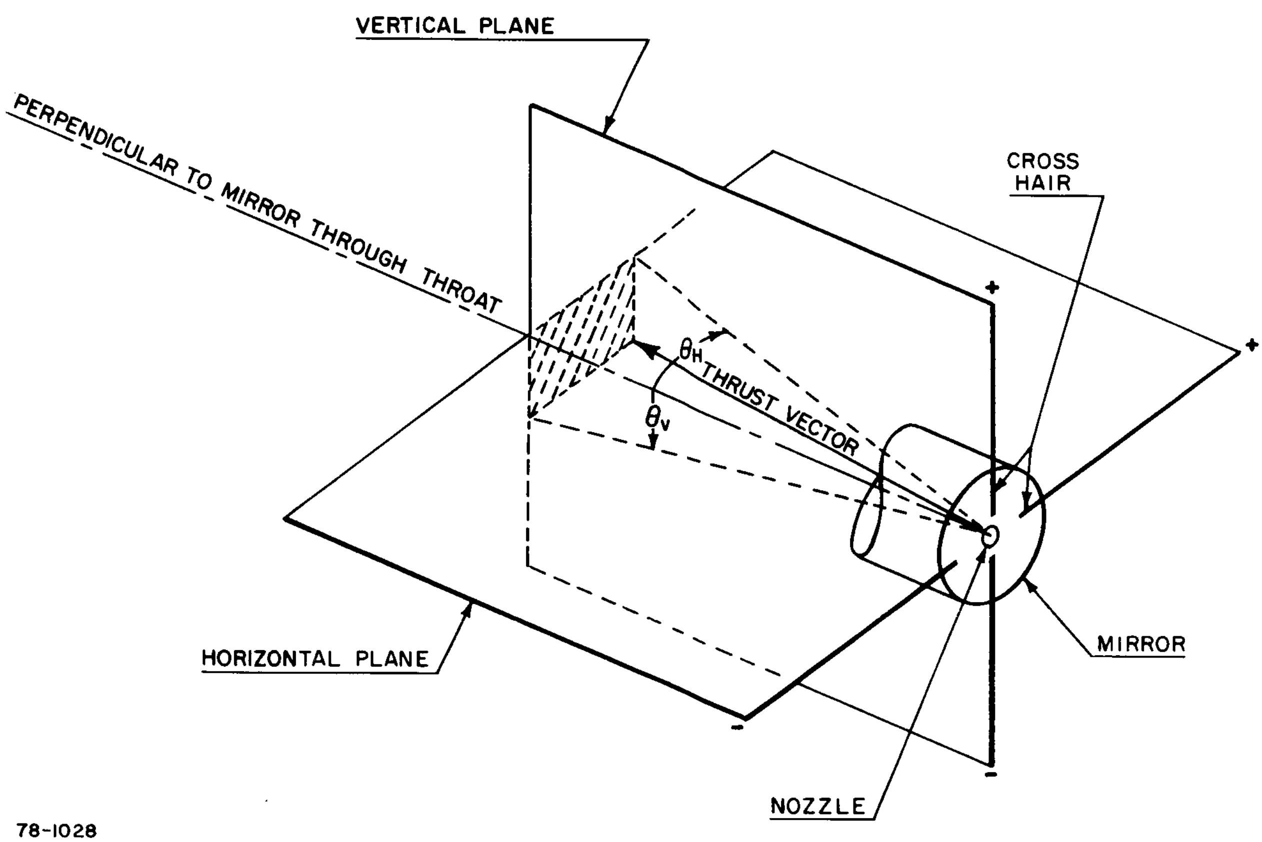


Figure D-1 THRUSTOR MIRROR/THRUST VECTOR RELATIONSHIP

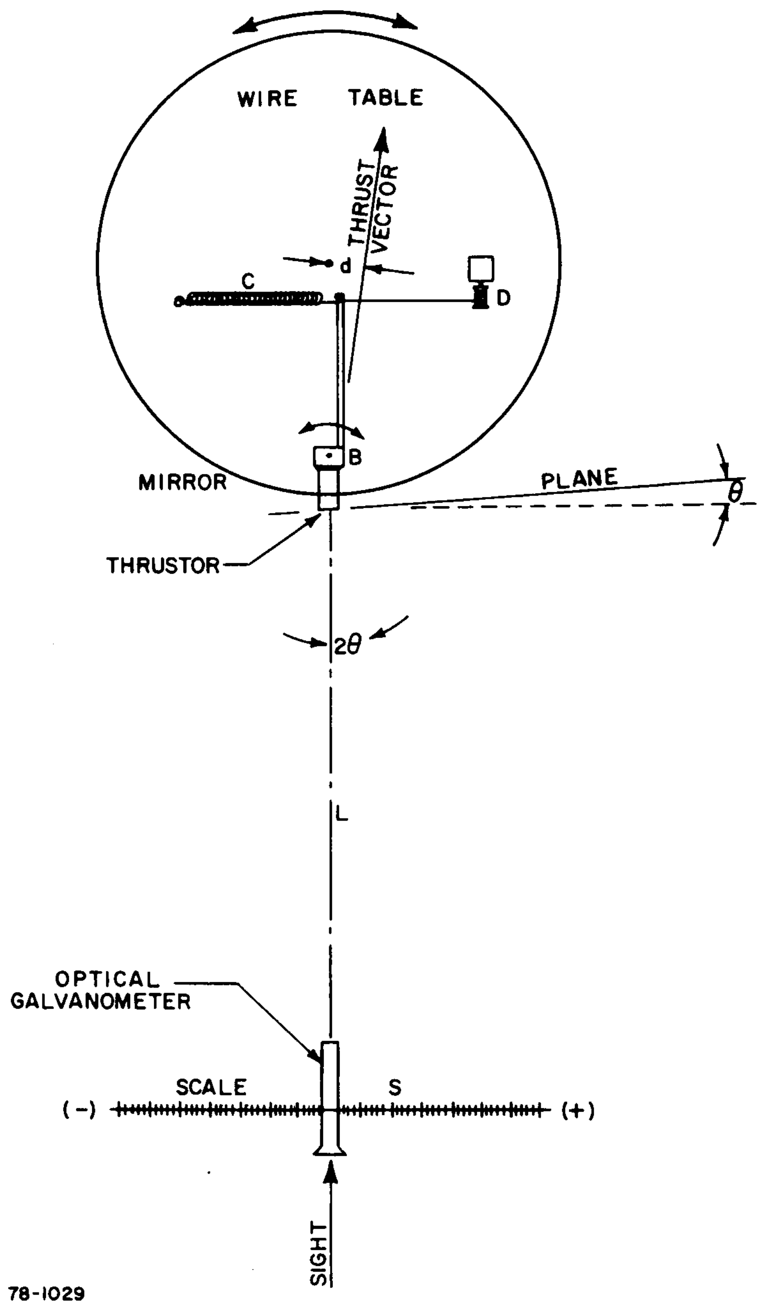


Figure D-2 SCHEMATIC OF VECTOR DETERMINING SYSTEM

APPENDIX E

QUALITY ASSURANCE AND SYSTEMS TEST PROCEDURES

Formal test procedures have been prepared for many of the components and subsystems. These test procedures are referred to as "Quality Assurance Test Procedures" or "QATP's." These documents, together with measurement of physical dimension and item serialization, are the principal elements of component and subsystem quality control (both for items obtained from vendors or fabricated and/or assembled in-house).

The QATP's used on this program are listed in Table E-I. Completed QATP's are included in the Data Log for the program, reference 3.

TABLE E-I

QUALITY ASSURANCE TEST PROCEDURES

STP	Item
SD-101 Rev. A	Bristol Pressure Switch Mod. C2069-1,2,3,4
SD-102 Rev. A	Pressure Transducer Mod. 1003-0151
SD-103 Amend. #2	Axial Solenoid Valve Mod. 1809001-41,44,20
SD-105 Amend. #1	Thermistor Mod. K816
SD-146	Carleton Relief Valve Mod. 1962001-7
SD-165	Power and Signal Conditioning Module 309180
SD-166	Station-Keeping Module 309130
SD-167	Supply Signal Conditioning Module 309229
SD-168	Logic Module 309214
Reference Only - (Procedure used as applicable by Engineering)	
SD-132 Rev. A	Transformer Assembly SSD100019,1,3; 100301,3,5
SD-107	Thrustor Characterization

Four Systems Test Procedures, "STP," were used in the program to characterize the system and to evaluate its performance during and following environmental qualification testing. These test procedures are listed in Table E-II. Completed STP's are included in the Data Log, reference 3.

TABLE E-II

SYSTEMS TEST PROCEDURES

STP	Test Description
SSD-1011	Qualification Test Plan
SSD-1012	Atmosphere Long Form Test
SSD-1013	Vacuum Long Form Test
SSD-1014	Systems Performance Test-Wire Table Facility

APPENDIX F

SINGLE-AXIS SYSTEM CALIBRATION

The supply, preplenum, plenum, and nozzle box pressure transducers were zero-balanced and calibrated versus Wallace and Tiernan gauges. These calibrations are shown in Figures F-1 through F-5. The thermistor telemetry channel was calibrated by applying known resistances at the thermistor input and entering the temperature from the resistance/temperature curve for each thermistor. The result of this calibration is shown in Figure F-6. It should be noted that this channel saturates at both negative and positive values.

The telemetry signal for the operation of the primary regulation valve was 2.46 to 2.50 volts. This valve often does not achieve steady-state, because of the short pulse width and generally slow response of the recording instrument.

Figure F-7 shows system input current versus telemetry output.

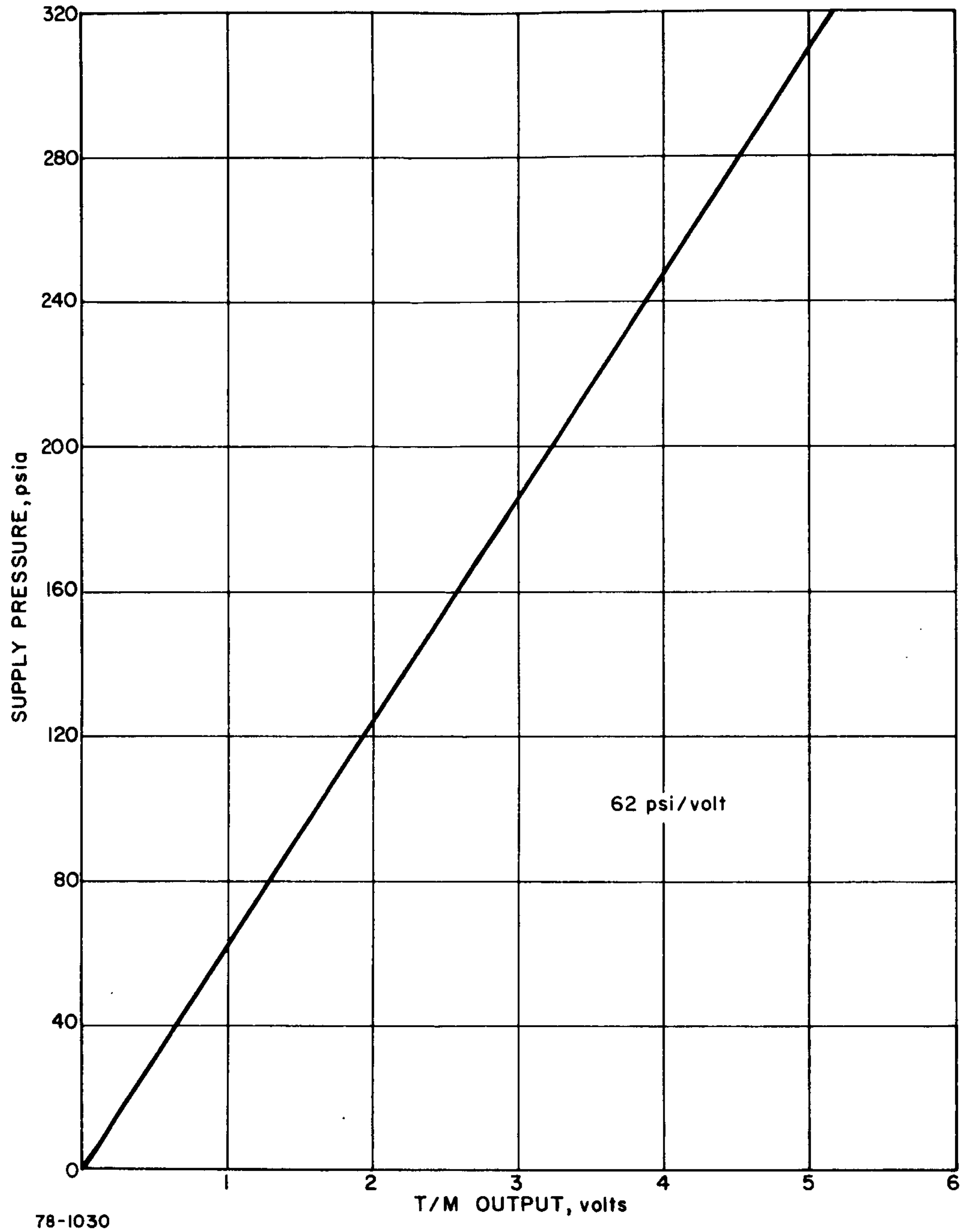


Figure F-1 SUPPLY PRESSURE VERSUS TELEMETRY OUTPUT

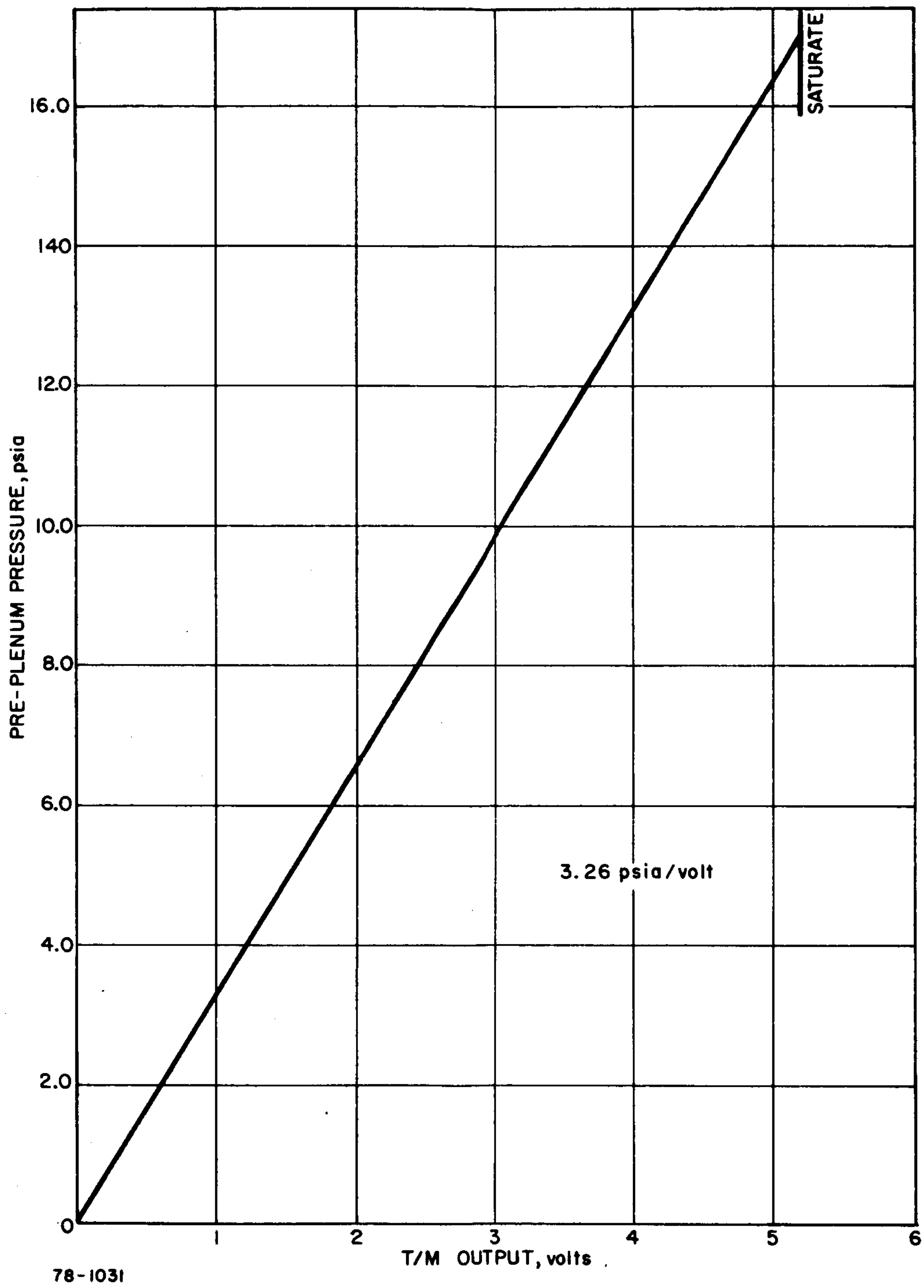


Figure F-2 PREPLENUM PRESSURE VERSUS TELEMETRY OUTPUT

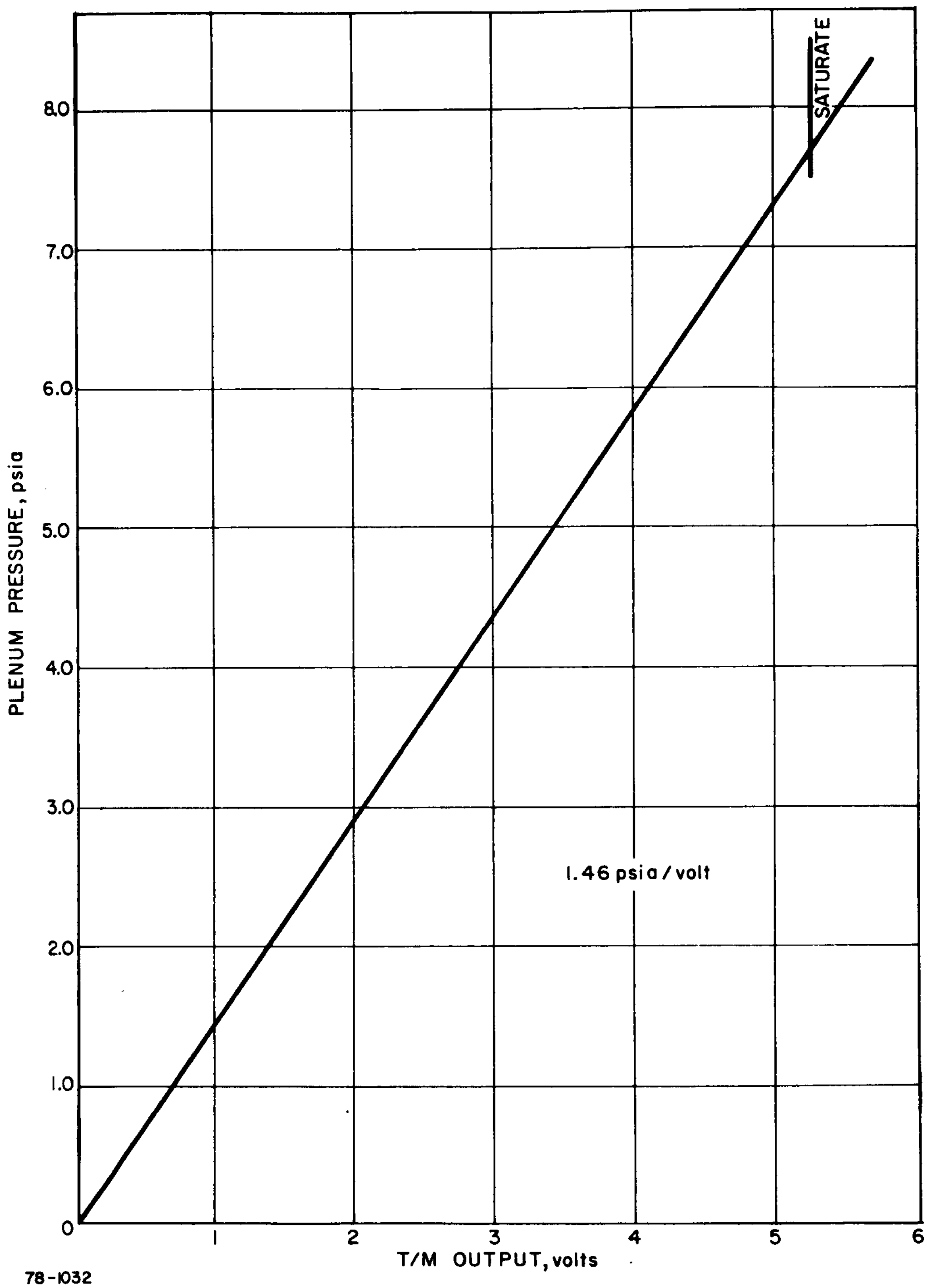
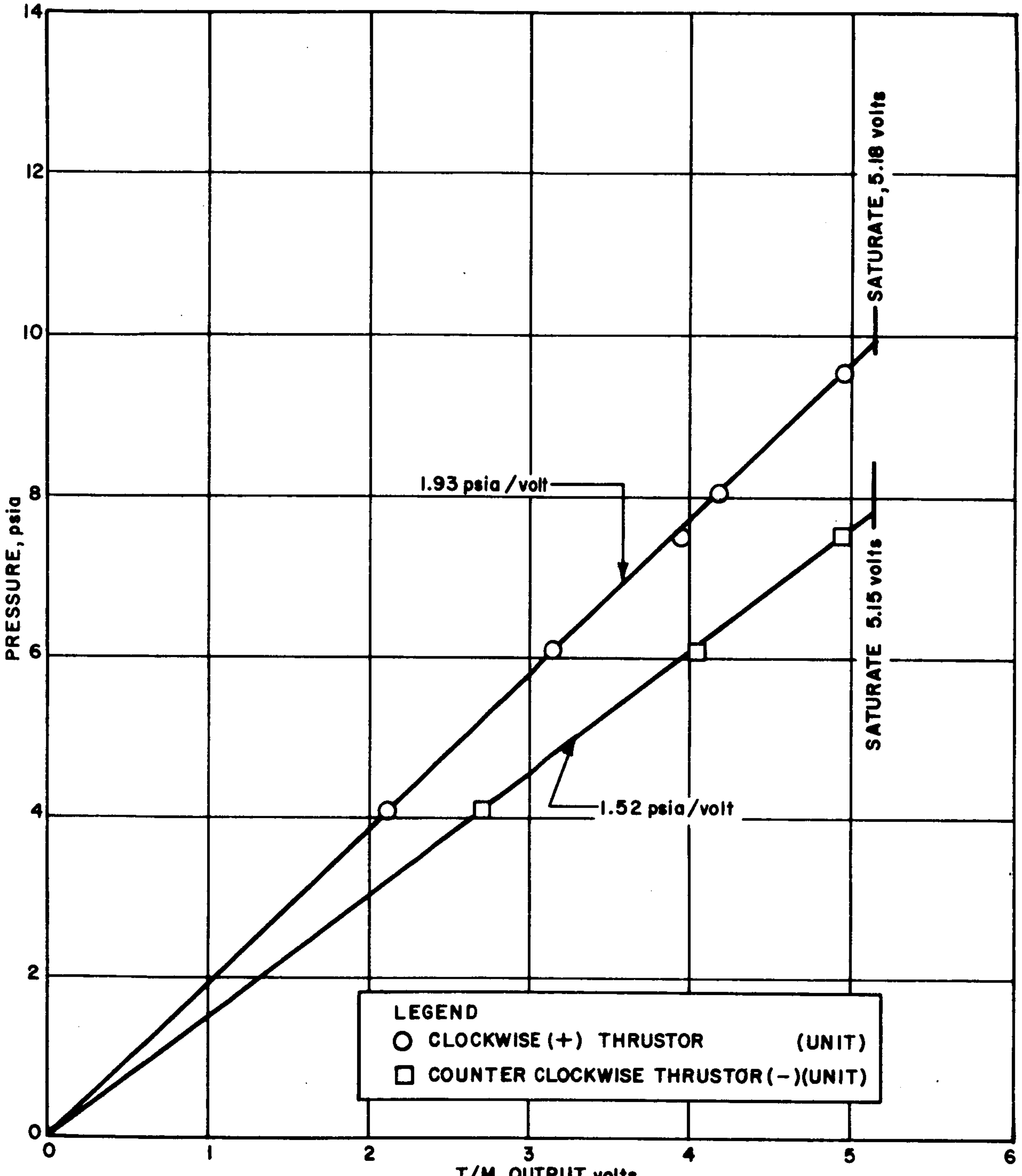
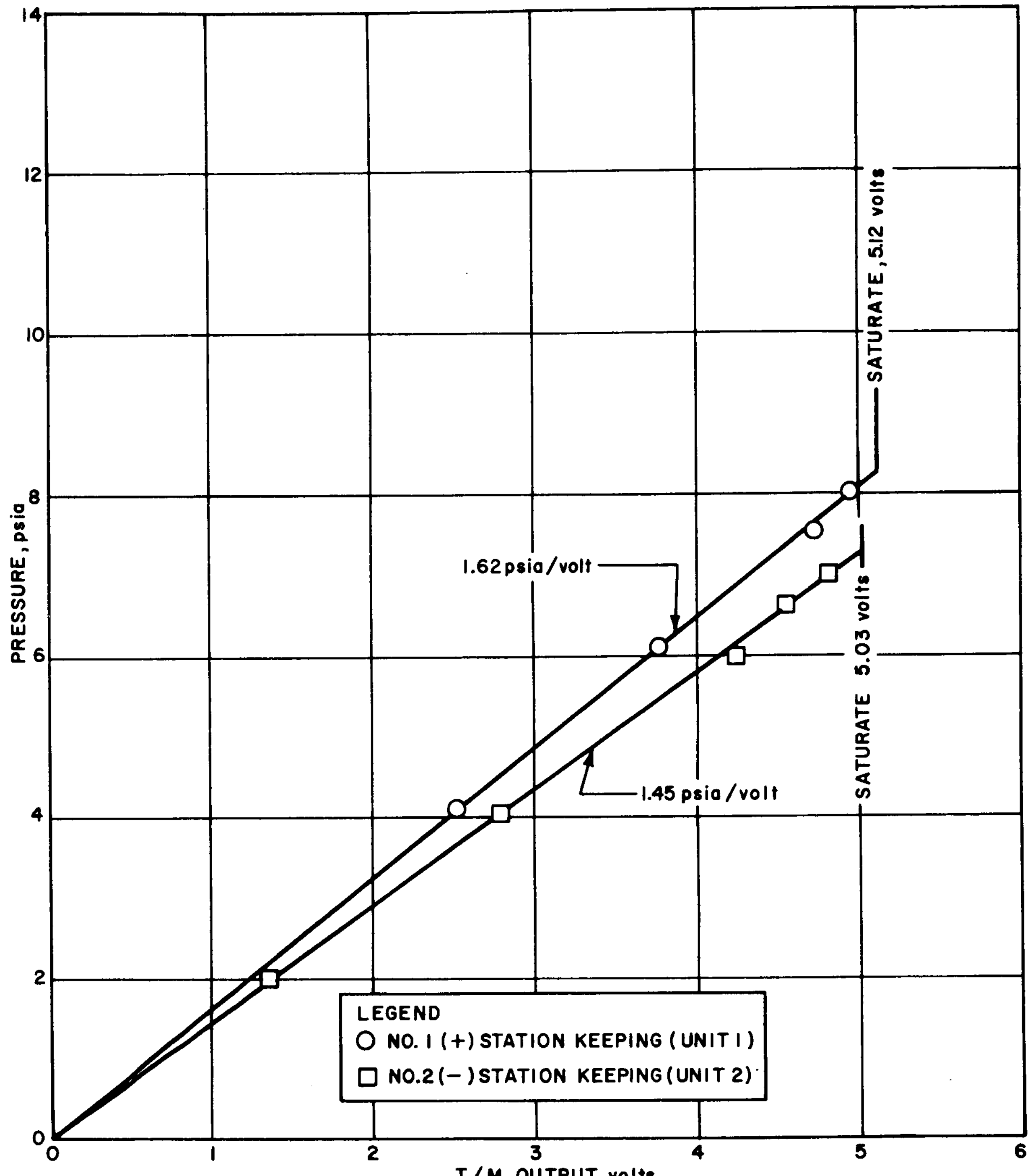


Figure F-3 PLENUM PRESSURE VERSUS TELEMETRY OUTPUT



78-1033

Figure F-4 ATTITUDE CONTROL THRUSTOR PRESSURES VERSUS TELEMETRY OUTPUT



78−1034

Figure F-5 STATION-KEEPING THRUSTOR PRESSURES VERSUS TELEMETRY OUTPUT

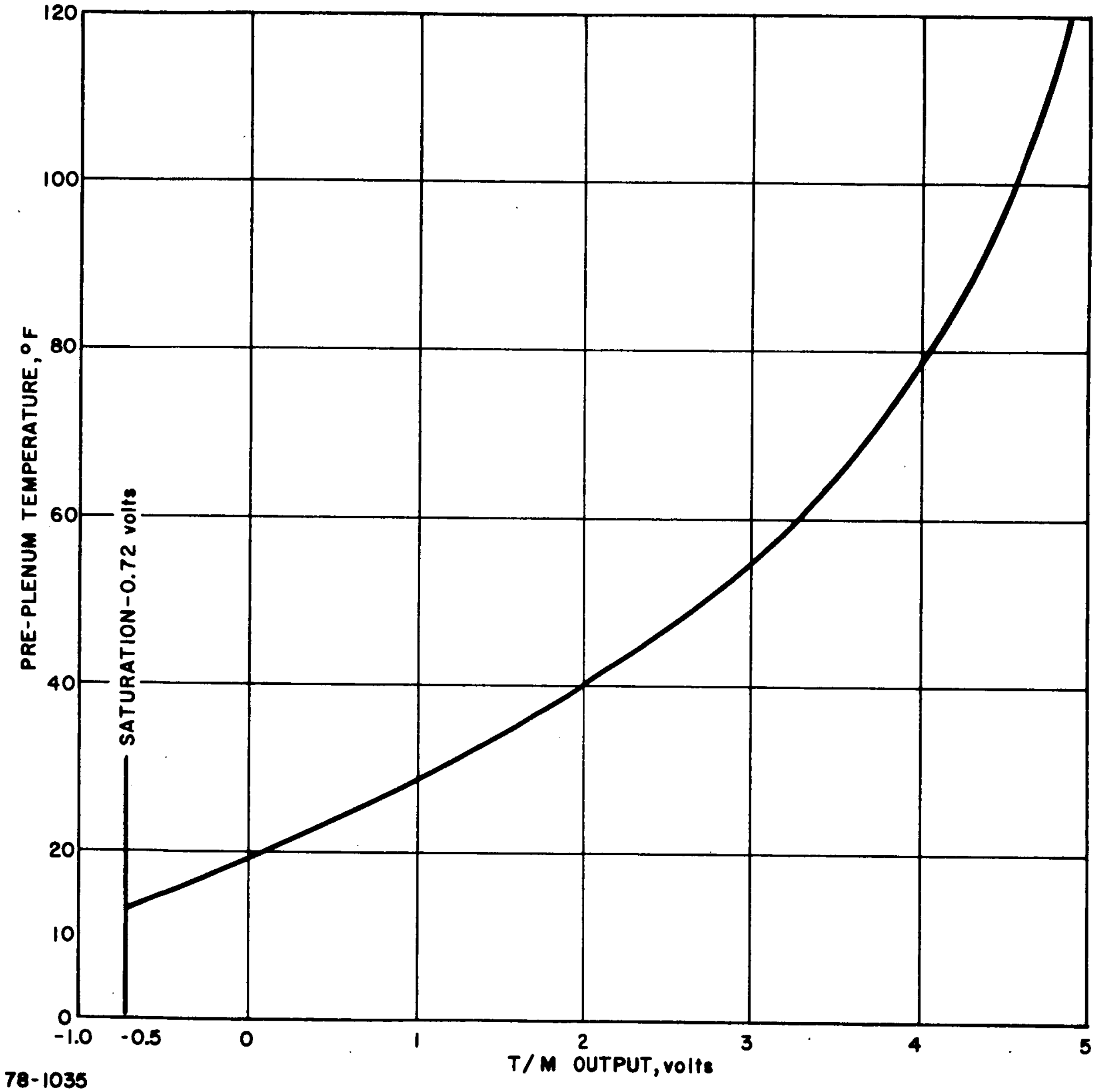


Figure F-6 PREPLENUM TEMPERATURE VERSUS TELEMETRY OUTPUT

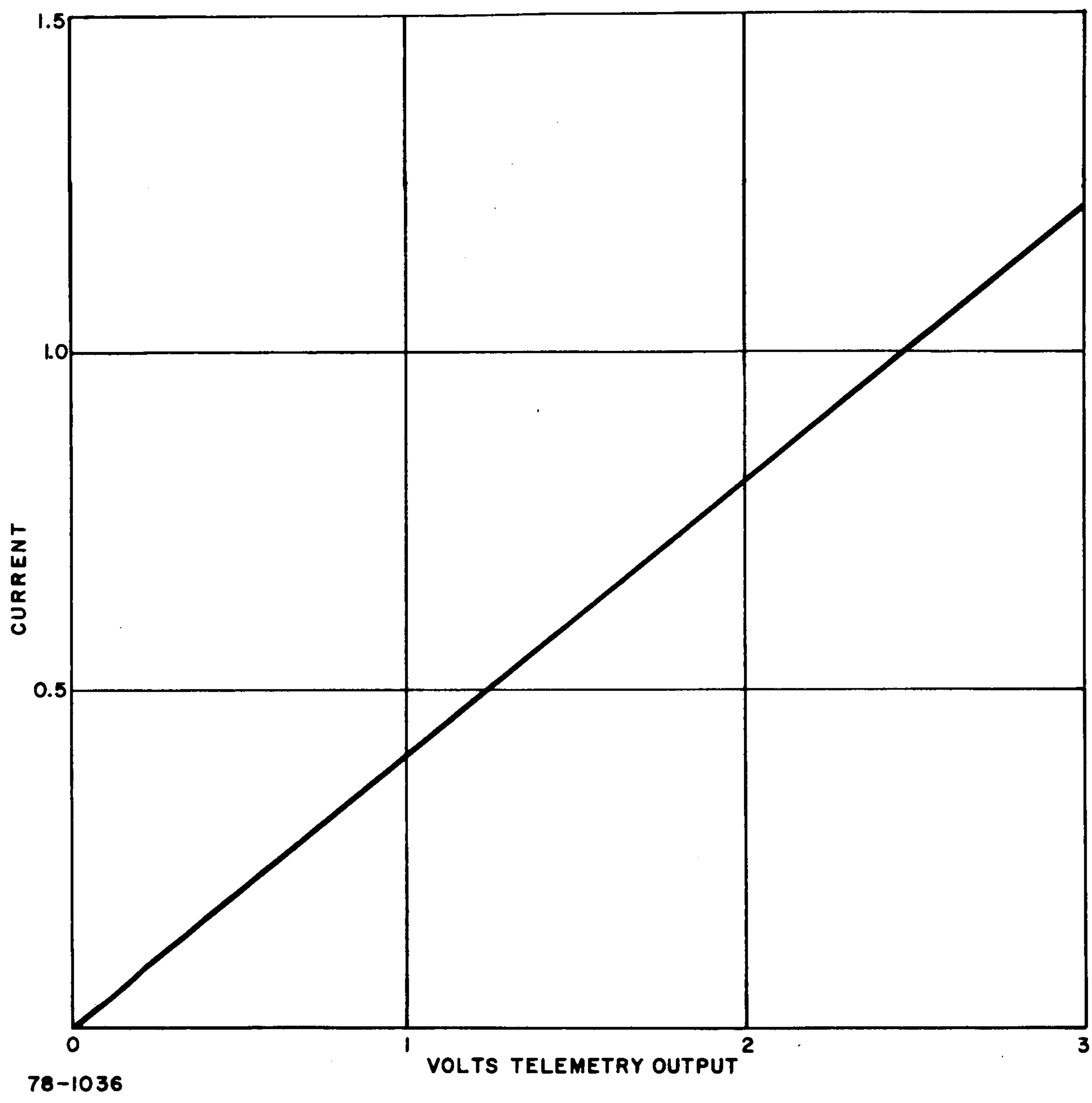


Figure F-7 SYSTEM INPUT CURRENT VERSUS TELEMETRY OUTPUT

APPENDIX G

ENVIRONMENTAL TEST DATA

Photographic and recorded data was taken for several of the environmental tests during system qualification. In most cases this information is self-explanatory

1. Thermal Storage

A complete single-axis system consisting of a propellant tank and regulation system, logic, power and signal conditioning, and four thrustor assemblies were temperature storage tested per the test conditions specified. These tests were run in an American Research Corporation, Arc-7, temperature chamber. Photographs of the system in the chamber, the test sequence, and test conditions are shown in Figure G-1. The system operated satisfactorily during the Long Form Test following each exposure.

2. Shock Tests

For the shock tests the propellant storage tank and regulation system was mounted on Avco's 500-pound shock test facility as shown in Figure G-2. The tank and regulation system was than subjected to three half-size shocks, 8.5 milliseconds in duration, with a peak of 38g. An oscillograph record of one of the shocks and a calibration run are shown in Figure G-2.

Each representative electronics module (potted) mounted on a dummy junction box and a thrustor assembly were also tested on the 500-pound shock facility. A photograph of the mounted equipment during the test and an oscillograph data record of one of the test shocks are shown in Figure G-3.

Following the tests, the system was reconnected together on an adjustment box with three other thrustor assemblies, and an Atmosphere Long Form Test run. This test indicated the system satisfactorily passed the shock testing.

3. Vibration Testing

As in the shock testing, the propellant storage tank and regulation system was tested separately from the electronics and a single thrustor assembly. Photographs of the system undergoing tests, the location of the control accelerometer, and the actual random vibration excitation are shown in Figures G-4 through G-9. It was noted during these tests that the solenoid valves did "dribble" when the test axis was parallel to the valve axis. The valves, however, sealed satisfactorily following the test. No visual damage to the tested components was observed and the complete system operated satisfactorily when connected together for an Atmosphere Long Form Test.

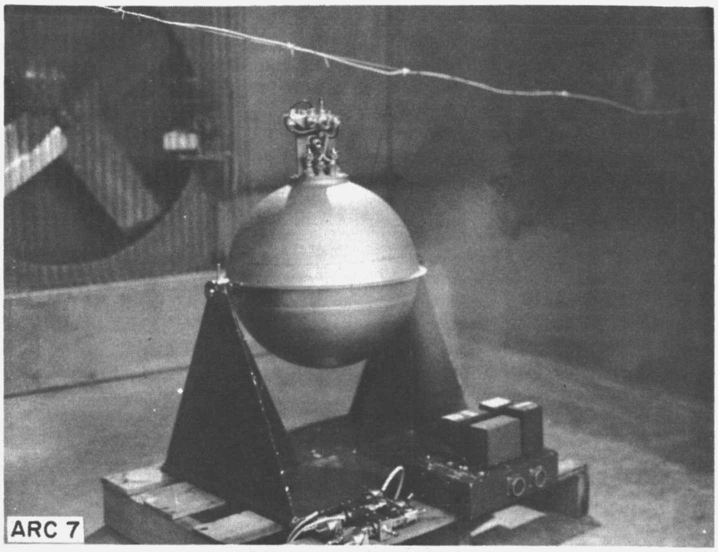
4. Thermal Vacuum

The full single-axis system and four thrustor assemblies were mounted in the Avco 10 ft x 10 ft thermal vacuum chamber shown in Figure G-10. The system was completely interconnected with power, telemetry, command, and monitoring thermocouple leads extending through the chamber wall to respective power supplies, controls, and data monitoring equipment. A close-up of the system in the chamber is shown in Figure G-11.

Figure G-12 indicates the location of the monitoring thermocuoples. A given test temperature was considered satisfactory when the averaged reading of the seven equipment thermocouple monitors was within 15 percent of the specified temperature and if no single one was off by more than 20°F. Wide temperature differences between the components were observed in the initial test phase. To rectify this problem the chamber was returned to atmosphere and a heated box enclosure was added to the base mounting plate to isolate the system from direct radiation cooling by the chamber's cold walls. No further temperature variance problem was encountered during the remaining portion of the test.

Five items of interest were observed during the Vacuum Long Form Testing in the chamber: 1) The system supply pressure following the vapor pressure-temperature relationship for ammonia permitted a test of the propellant regulation system at three different supply pressures; the system performed satisfactorily at each. 2) The Micro-Systems pressure transducer indicated a tendency to have a zero shift when the environment temperature was changed. It was noted that the shift could be calibrated and that it would usually return to normal when ambient temperature was restored. During this test the plenum pressure transducer shifted to a saturated telemetry output throughout the test, but as the preplenum and the nozzle box transducers operated satisfactorily the test was not interrupted. 3) The significant thermal capacity of the liquid ammonia propellant was demonstrated when the test required a change of the system temperature. 4) No system abnormalities were observed during the short attitude control thrustor operations or the thirty-minute station-keeping operations. 5) One somewhat undesirable system feature which, however, would not be a problem in space, is that the system would respond to a large electrical noise pulse (e.g., the starting and stopping of laboratory electrical equipment), by changing the position of many of the system's electronic flip-flops; i.e., if a thrustor valve flip-flop was set at ON, it would be reset to OFF and visa-versa.

A summary of Vacuum Long Form telemetry taken during the Thermal Vacuum Test is shown in Table G-I.



a. COLD STORAGE TEST
-22°F 6 hours

b. SYSTEM OPERATION
ATMOSPHERE LONG FORM STP SSD-1012
77°F

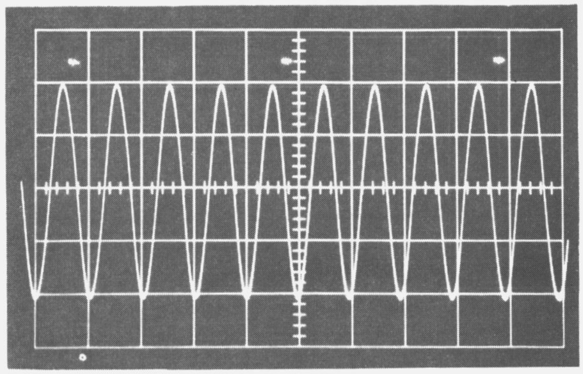
c. HOT STORAGE TEST
140°F 6 hours

d. SYSTEM OPERATION
ATMOSPHERE LONG FORM STP SSD-1012
77°F

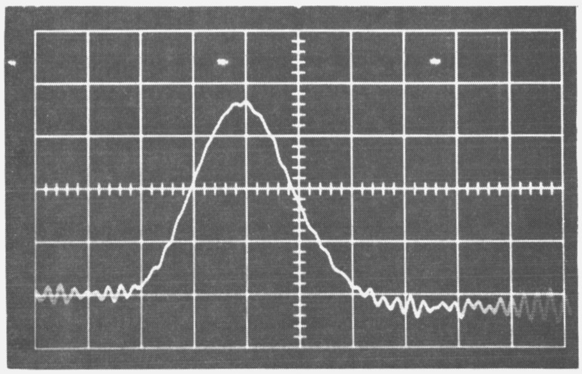
78-1037

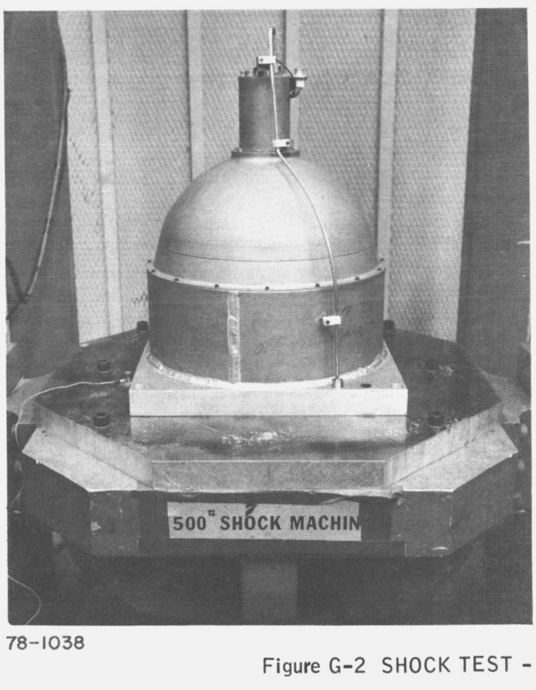
Figure G-1 TEMPERATURE STORAGE TESTS - COMPLETE SINGLE-AXIS SYSTEM, 7 TO 9 OCT 1967

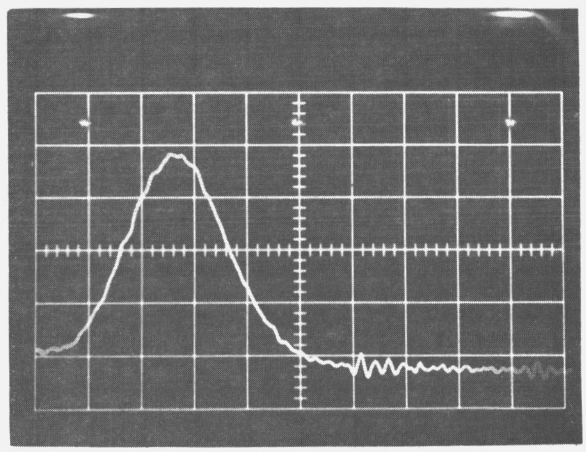
CALIBRATION
10g /cm
1ms /cm
0.2 -4000cps



CALIBRATION
10g /cm
1ms/cm
0.2-2000cps
2.5in. D.H.
901 451-16 PAD
175lb. LOAD



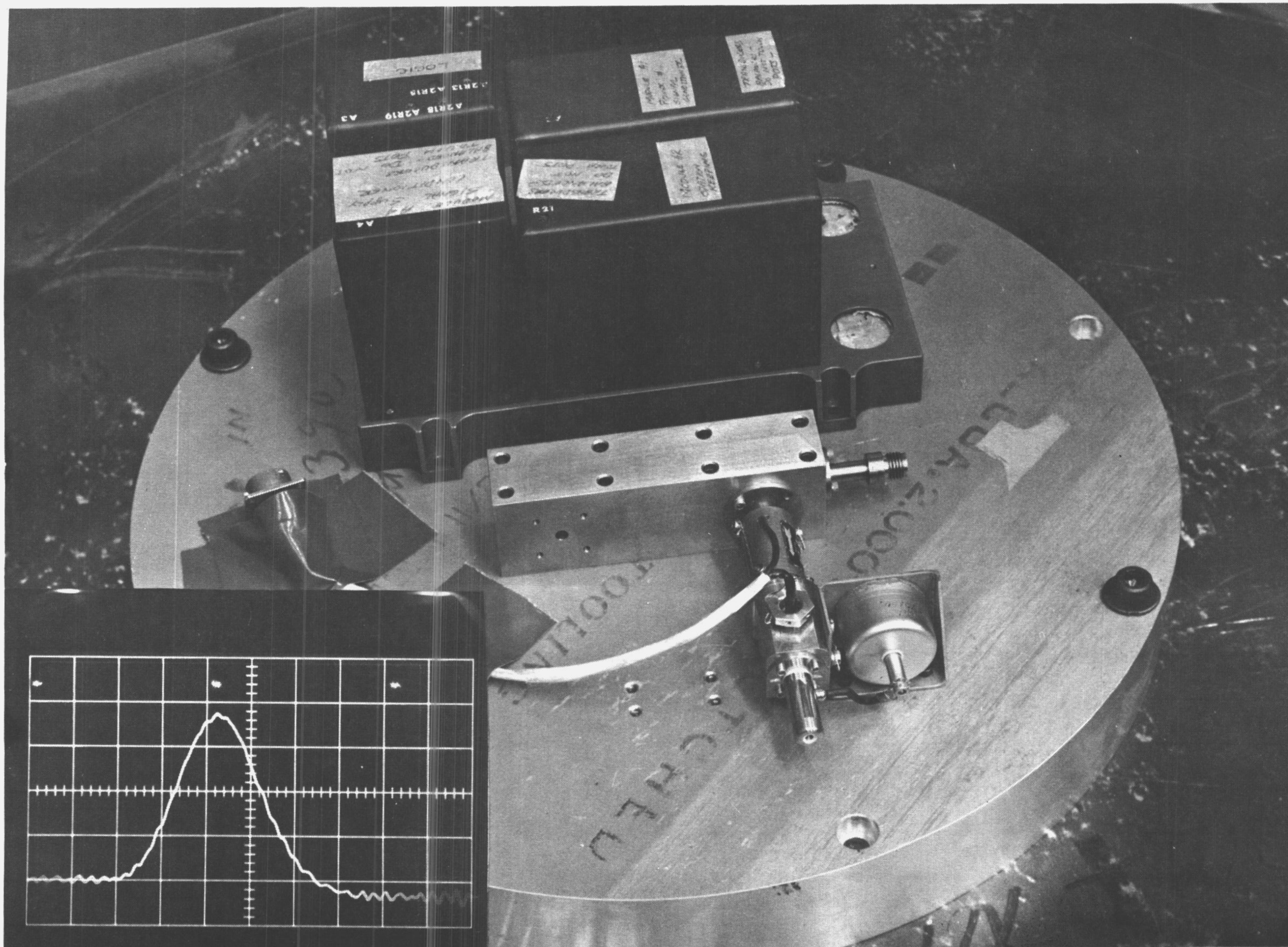




38g 8.5ms 1/2 sine
3 SHOCKS

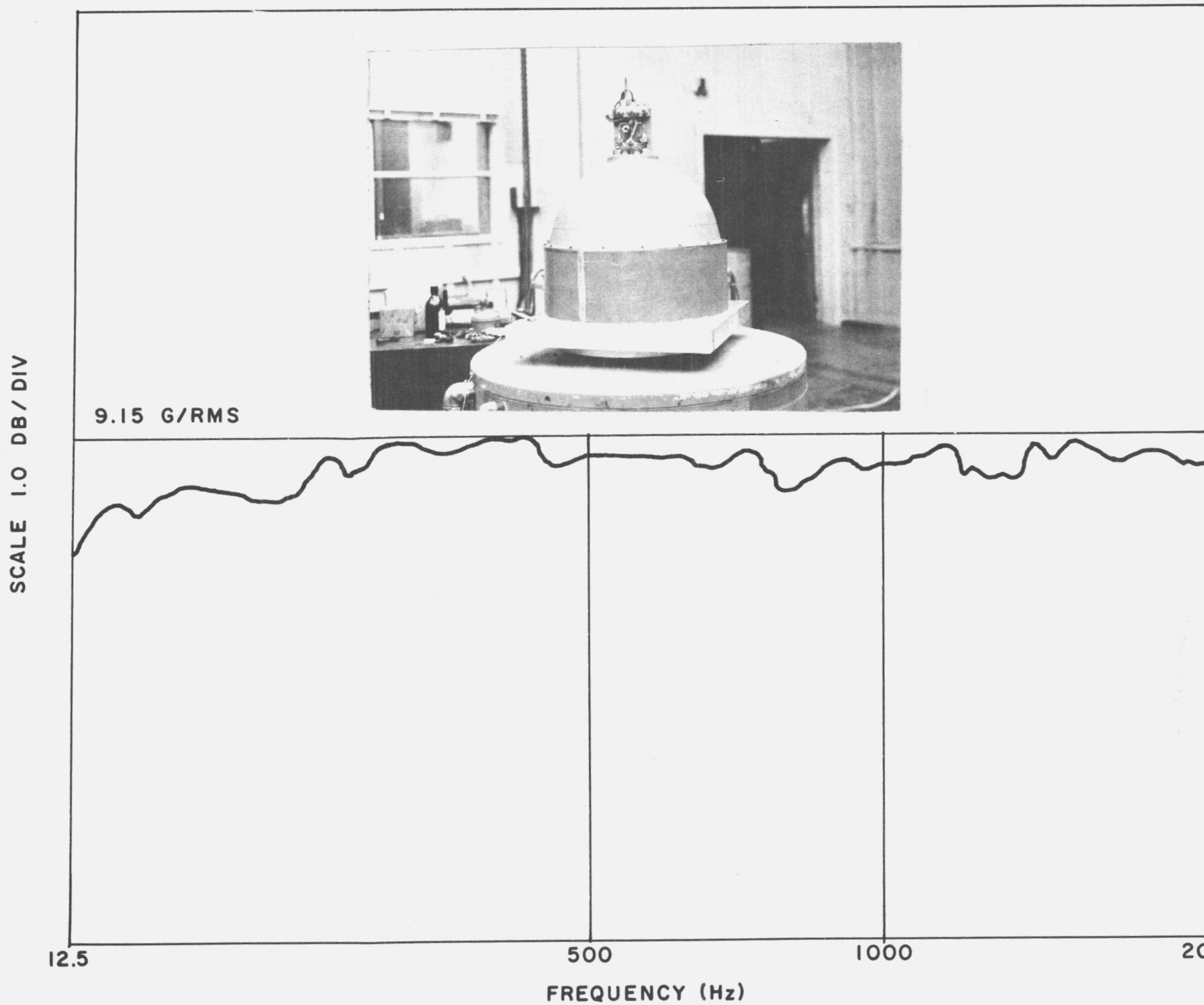
78-1038

Figure G-2 SHOCK TEST - PROPELLANT STORAGE AND FEED SYSTEM,
9 OCT 1967



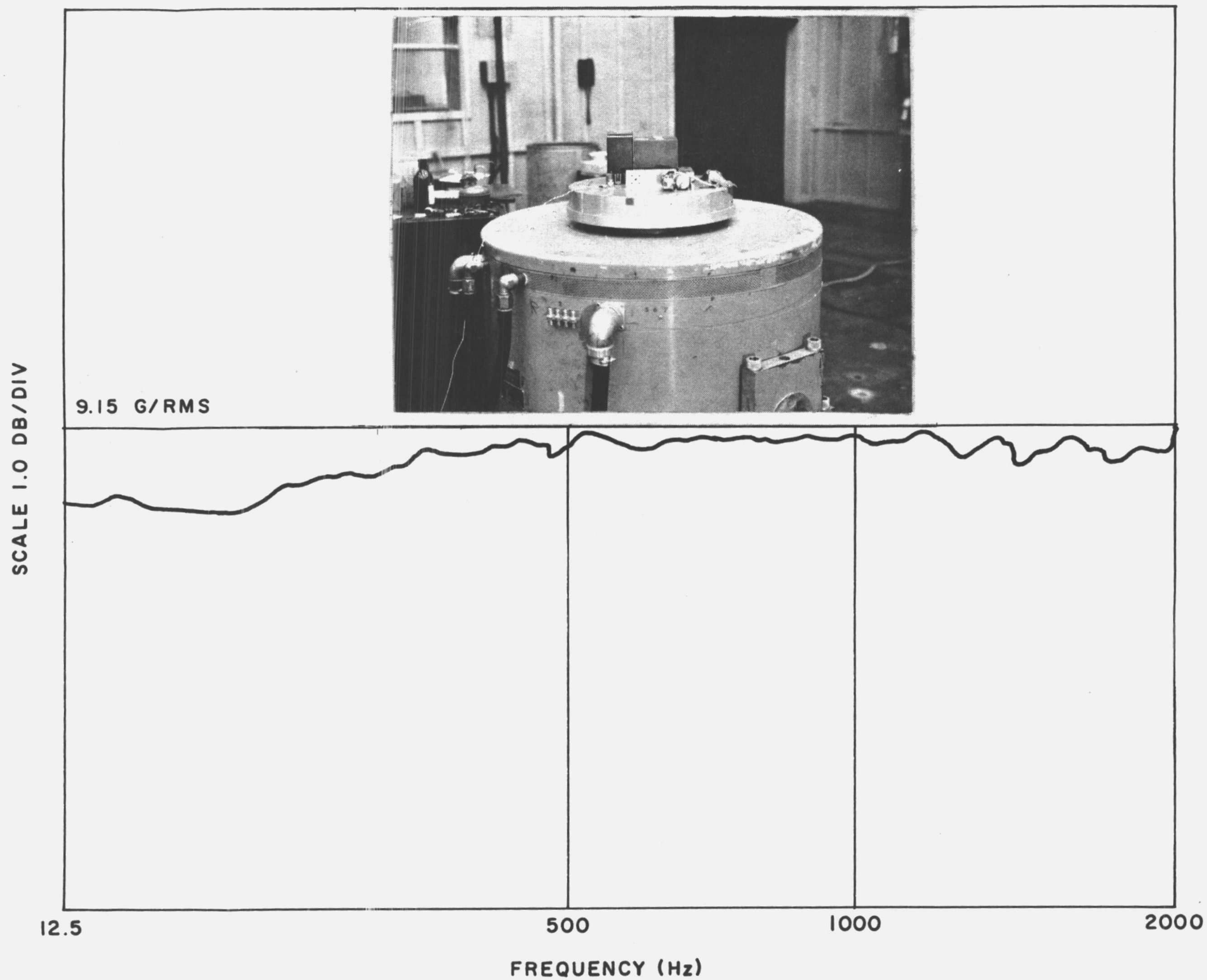
18673 A

Figure G-3 SHOCK TEST - ELECTRONICS AND THRUSTOR ASSEMBLY, 10 OCT 1967



78-1039

Figure G-4 RANDOM VIBRATION, LONGITUDINAL AXIS (TANIC) 57 POUND AMMONIA SYSTEM, 9 OCT 1967



78-1040

Figure G-5 RANDOM VIBRATION, LONGITUDINAL AXIS (ELECTRONICS AND THRUSTOR
57 POUND AMMONIA SYSTEM, 10 OCT 1967

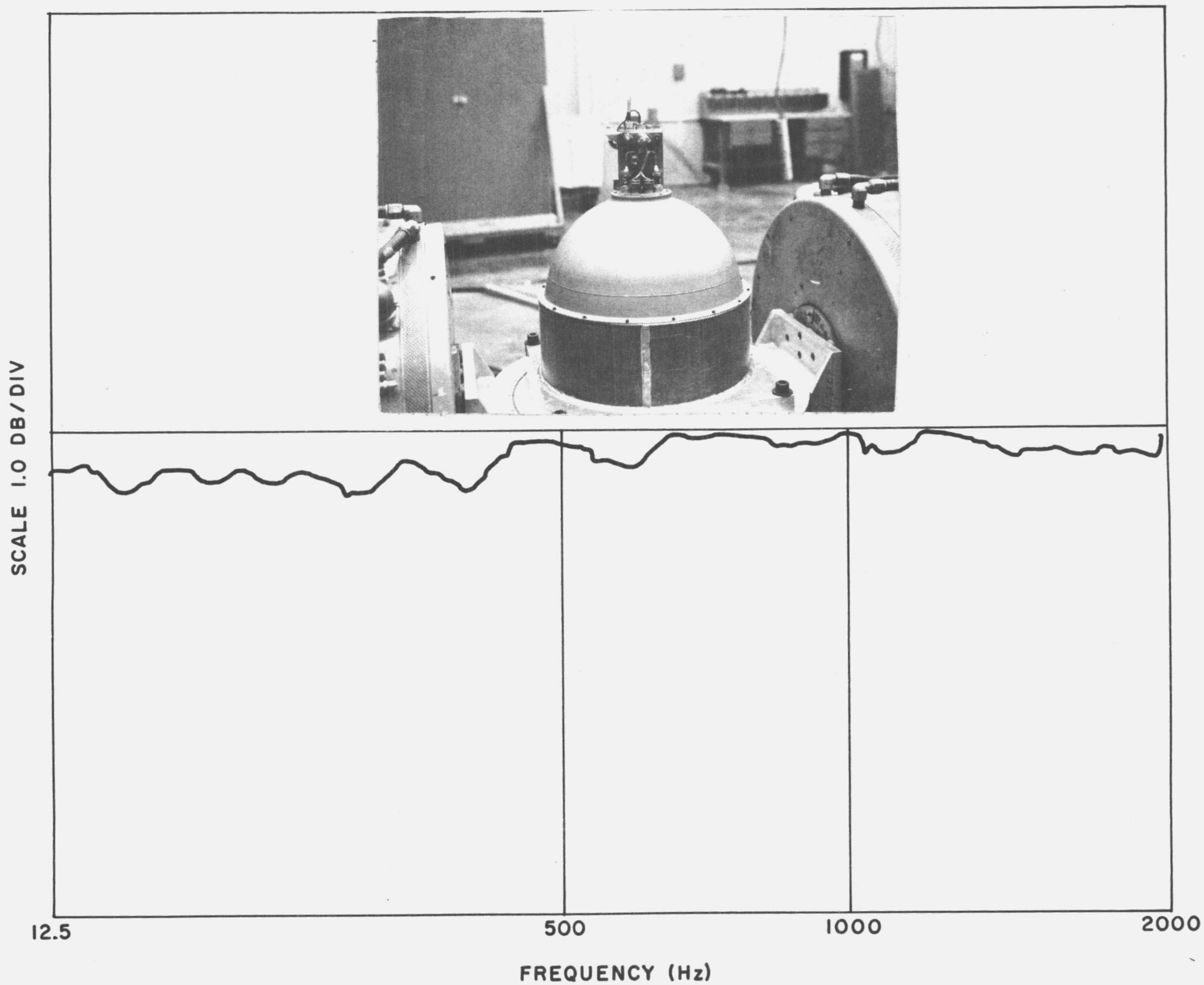
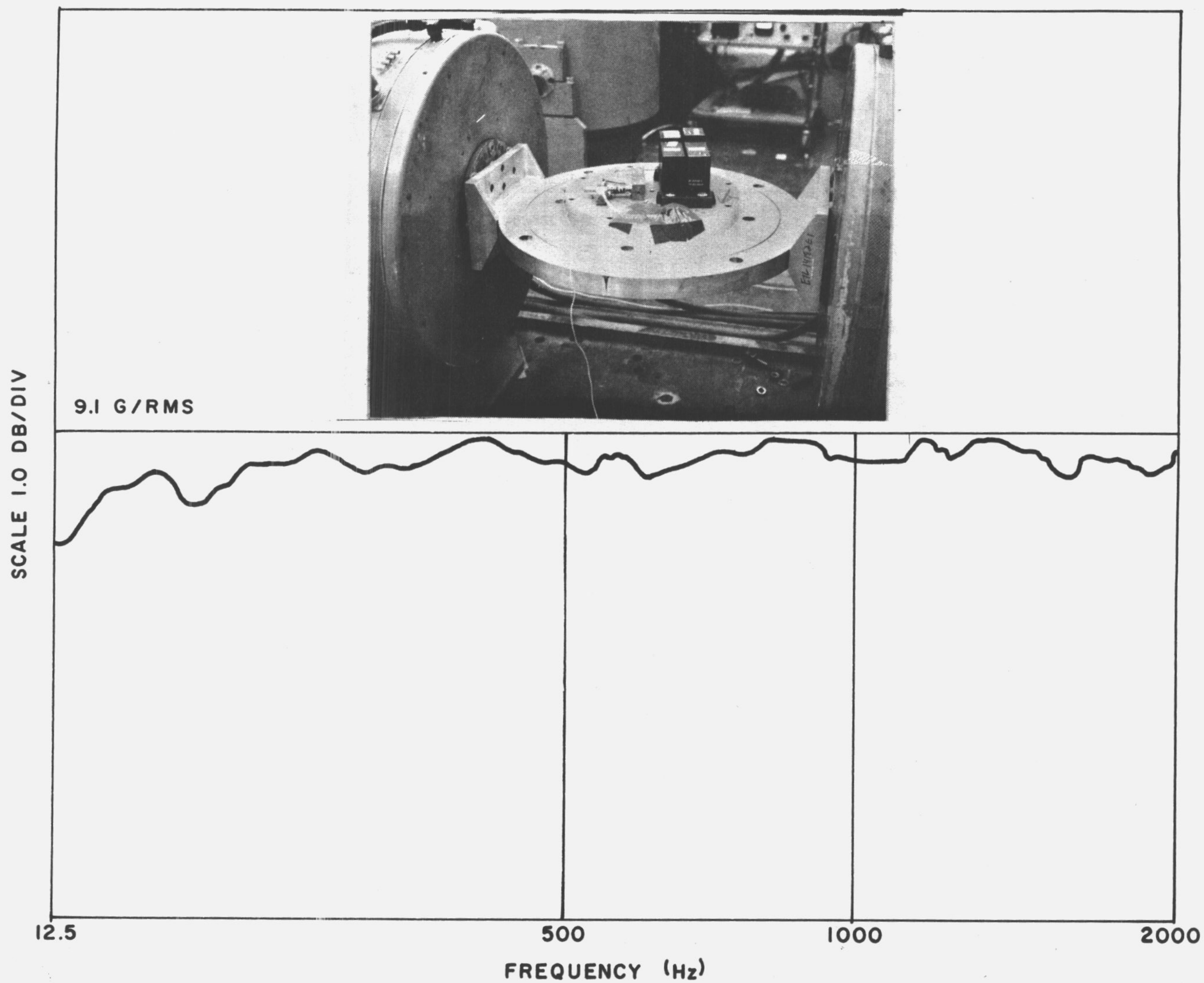
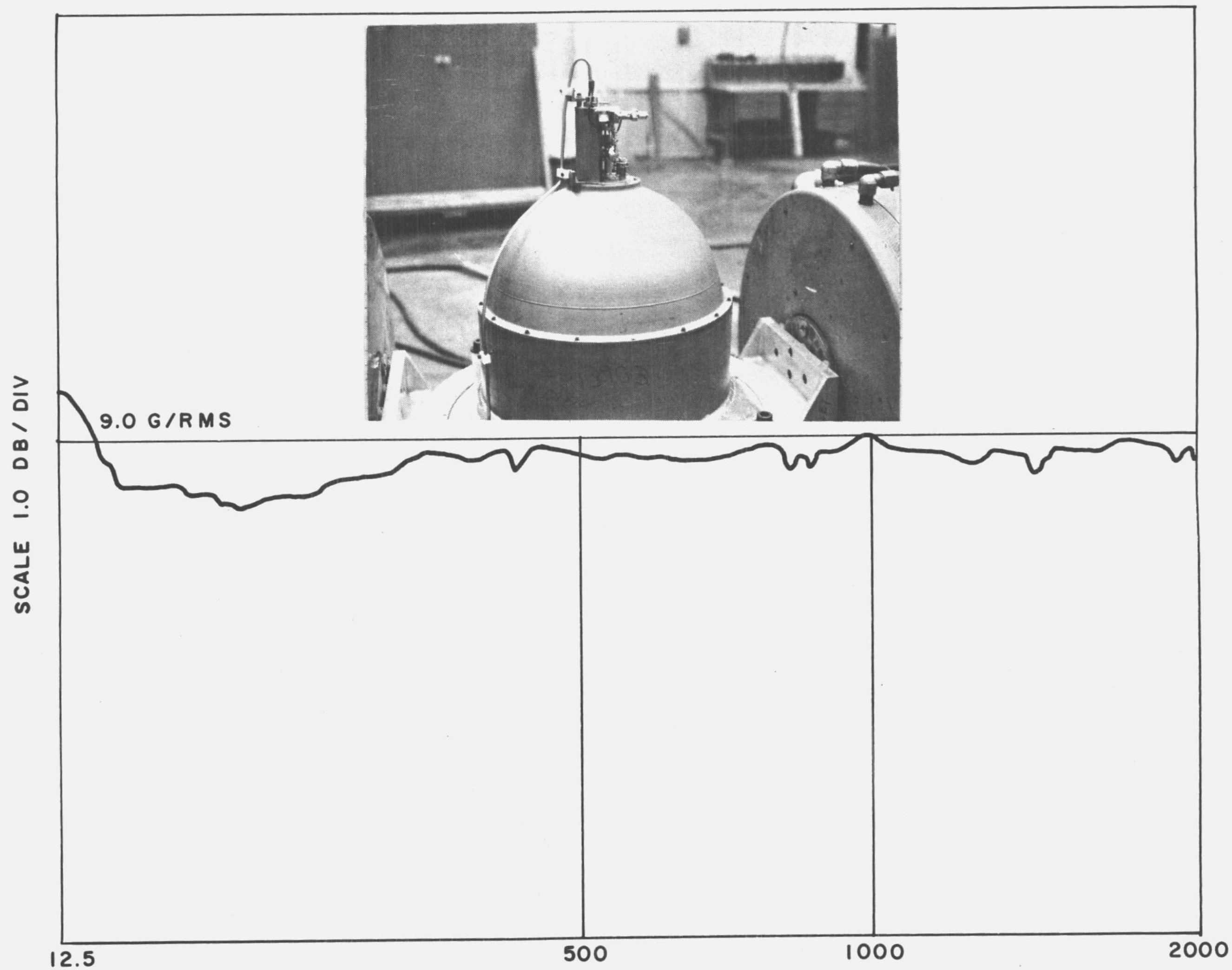


Figure G-6 RANDOM VIBRATION, 1ST LATERAL AXIS (TANK) 57 POUND AMMONIA SYSTEM, 10 OCT 1967



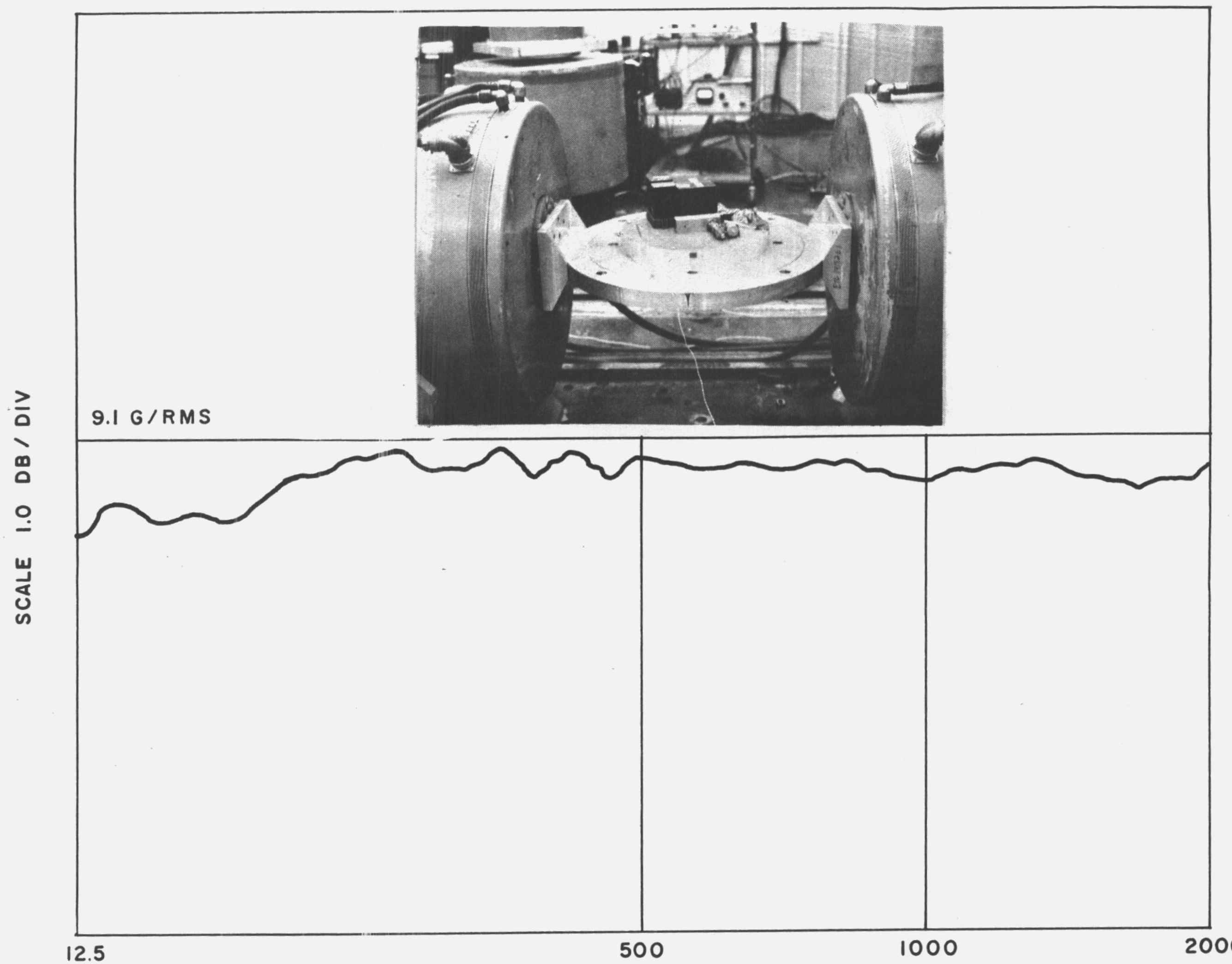
78-1042

Figure G-7 RANDOM VIBRATION, 1ST LATERAL AXIS (ELECTRONICS AND THRUSTOR)
57 POUND AMMONIA SYSTEM, 10 OCT 1967



78-1043

Figure G-8 RANDOM VIBRATION, 2ND LATERAL AXIS (TANK) 57 POUND AMMONIA SYSTEM, 10 OCT 1967



78-1044

Figure G-9 RANDOM VIBRATION, 2ND LATERAL AXIS (ELECTRONICS AND THRUSTOR)
57 POUND AMMONIA SYSTEM, 10 OCT 1967

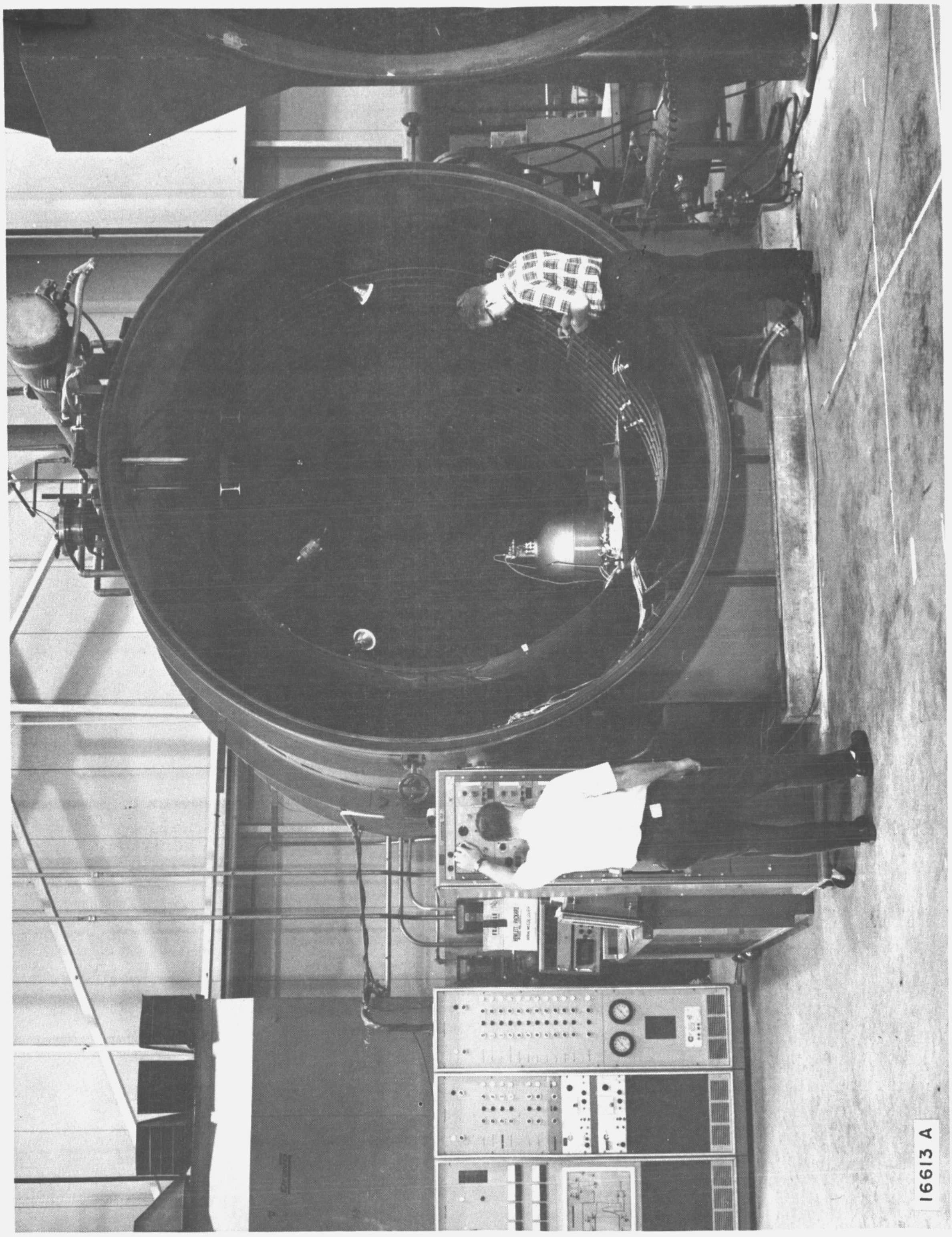


Figure G-10 10 FT BY 10 FT THERMAL VACUUM FACILITY WITH SINGLE-AXIS SYSTEM

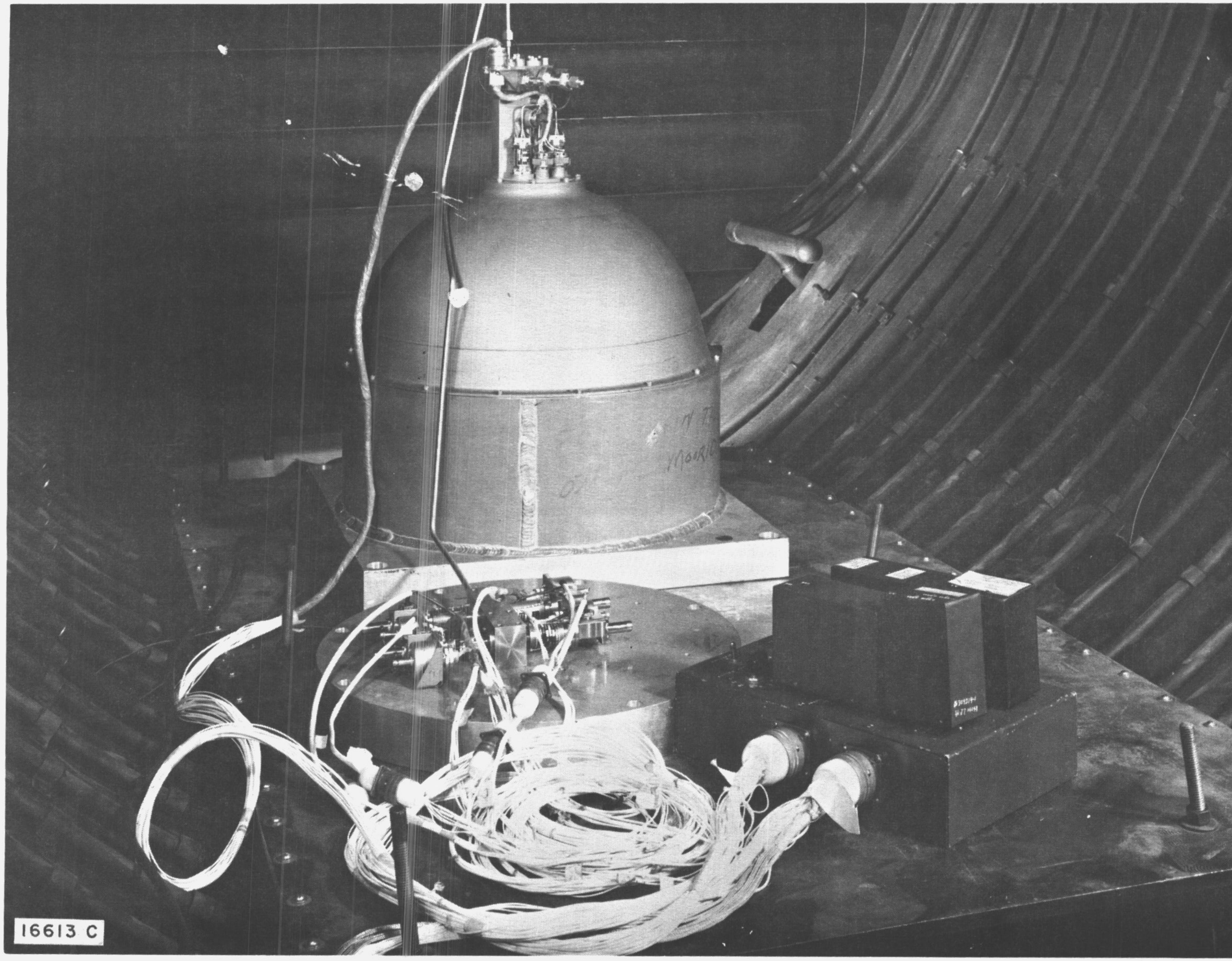


Figure G-11 SINGLE-AXIS CONTROL SYSTEM INSTALLED IN THERMAL VACUUM CHAMBER

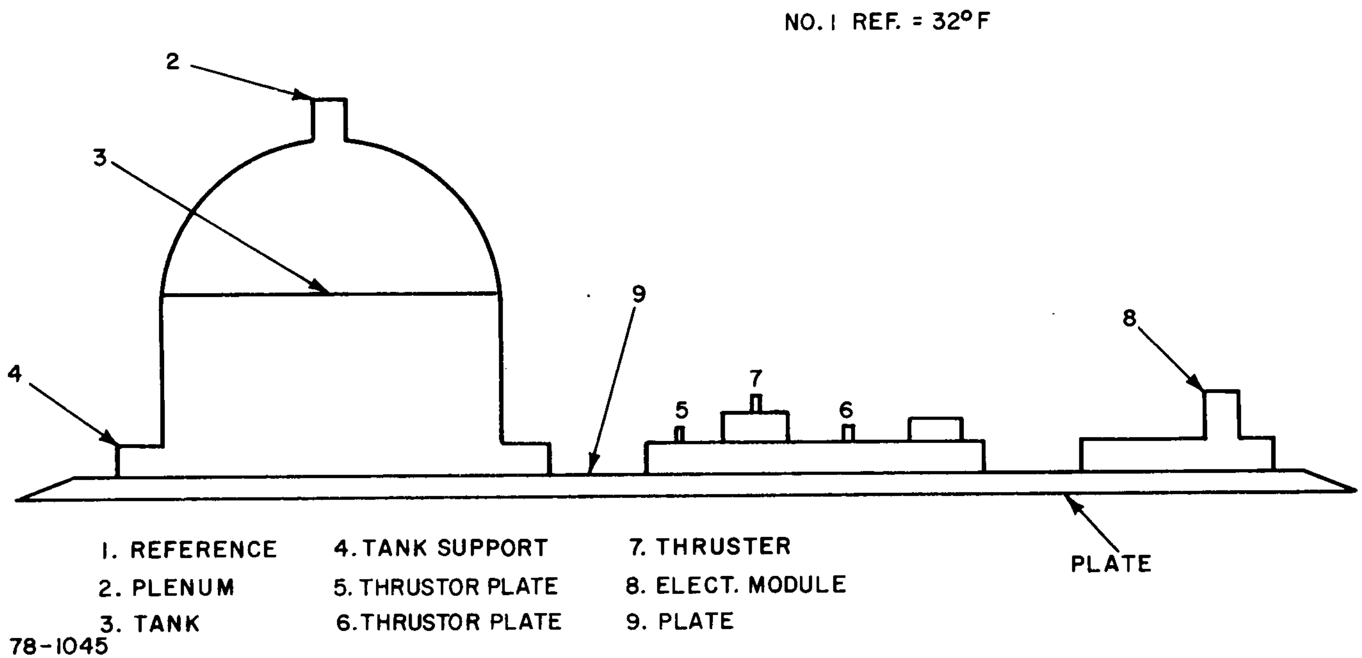


Figure G-12 THERMOCOUPLE LOCATIONS ON SINGLE-AXIS SYSTEM DURING THERMAL VACUUM TEST

TABLE G-I

THERMAL VACUUM LONG FORM DATA*

Telemetered Data	Phase I Cold Soak: 22°F		Phase II Hot Soak: 118°F		Phase III Ambient Temperature: 70°F	
	1st Vacuum Long Form	2nd Vacuum Long Form	1st Vacuum Long Form	2nd Vacuum Long Form	Vacuum Long Form Start	Vacuum Long Form Completion
Plenum Temperature	15°F	14°F	114°F	97°F	68°F	59°F
Supply Pressure	80 psia	73 psia	163 psia	181 psia	184 psia	132 psia
Plenum Pressure	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation
Preplenum Pressure	7.9 psia	8.0 psia	10.0 psia	10.1 psia	8.6 psia	8.6 psia
CW Nozzle Pressure	4.3 psia	4.6 psia	4.8 psia	4.8 psia	4.8 psia	5.1
Other Nozzle Box Pressures	0	0	0	0	0	0
System Current Input	1.5 amps	1.4 amps	0.7 amp	0.6 amp	1.1 amps	1.0 amp
Primary Regulation Value	Pulsing	Pulsing	Pulsing	Pulsing	Pulsing	Pulsing
CW Heater Current	1.51	1.64	1.85	1.84	2.22	2.26
Heater Currents of Other Thrustors	0	0	0	0	0	0
CW Heater Voltage	2.98	2.98	3.13	2.71	3.03	3.03
Heater Voltages of Other Thrustors	0	0	0	0	0	0

*Note: Data shown represents system operating with the clockwise attitude control thrustor on hot (T_2 and T_{17}).

APPENDIX H

ATTITUDE CONTROL THRUSTOR PERFORMANCE MEASURED DURING SYSTEM PERFORMANCE TESTS

The complete single-axis system is mounted on the wire supported platform for the initial and final System Performance Tests. This platform is instrumented with a rate gyro system for determination of the change of angular velocity of the platform. During the System Performance Test, the moment of inertia of the platform and the installed system is determined by the method described in QATP-107, Data Log, reference 3.

During the initial System Performance Test the loaded platform moment of inertia was determined to be 41.75 slug-ft^2. Recorded data of the change of the platform's angular velocity, measured by the rate gyro, during the attitude control thrustor firings and the measured moment of inertia indicate the CW thrustor to be performing at 330 μ lb of thrust and the CCW thrustor at 350 μ lb. (Thrustor performance levels are given in Section IV.D.2.)

During the final performance the loaded platform had a measured moment of inertia of 42.5 slug-ft^2. The performance of the CW thrustor was 230 μlb and that of the CCW thrustor was 270 μlb. (Thrustor performance levels are given in Section IV.D.2.)

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